MOISTURE TRANSPORT IN ATTIC SPACES LOCATED IN HOT-HUMID CLIMATES

By

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Current trends in residential-style construction have included techniques that utilize a non-vented attic space. A proposed advantage of this technique is that it could reduce the in-flow of moisture-laden air into attic spaces. However, little research has been done relating this aspect of construction to moisture transport in hot-humid climates.

A full-scale test facility was constructed to study many aspects of typical residential construction materials and techniques. The Building Products Test Facility is located on the University of Florida's Gainesville campus. This facility was used for the purposes of this investigation to provide insight into moisture transport phenomena related to attic spaces (vented, unvented, flat ceiling and cathedral) in a hot-humid climate.

A one dimensional moisture transport model was constructed and evaluated using boundary condition data obtained from a full-scale facility located in a hot-humid

climate. This model was evaluated with global environmental conditions and homogeneous building materials. Moisture transport rates obtained with the model were then compared to rates obtained from actual installed conditions of common building materials and boundary conditions associated with early morning saturated dewpoint conditions. These rates were much higher than those obtained in the first case. In addition, comparisons of long-term moisture contents for roof sheathing were presented for measured and derived values.

Additional data were obtained that described a removal mechanism for the moisture transported through the roof structure. The mechanism was based on continuous soffit and ridge vent structures.

The results of this study show that moisture moves through a shingle roof boundary driven by nighttime cooling followed by solar heating. Furthermore, current attic venting practices provide a removal mechanism for this moisture flow.

CHAPTER 1
INTRODUCTION

Moisture transport within residential structures has been studied and commented on throughout recorded history. Excessive moisture can cause many natural building materials to rot and decay with significantly reduced lifetimes as a result. Excess moisture within a structure can also lead to outbreaks of mold and mildew in the living space. While this is a topic of great discussion in the popular and professional literature, reference to mold and mildew can be found in Leviticus 14: 35-48, generally thought to have been written nearly 3,500 years ago.

The systematic study, or science, of building construction has generally developed first in cold-climate regions. This was due in part to the difficulty in maintaining general living conditions in cold temperature extremes as opposed to those found in warmer climates. Modern building materials and techniques coupled with the freeze and thaw behavior of snow-laden roofs soon led to the development of requirements for attic ventilation. High indoor humidity levels within conditioned spaces of such structures also led to wall cavity vapor barrier requirements.

The post World War II population of Florida and other southern coastal regions has grown at a much faster rate than the United States has as a whole. Since 1950, for example, the population of Florida has increased at an average annual rate of 3.6%. During the same period, the population of the United States increased at an average annual rate of not quite 1.3%. In overall terms, the population of Florida in the post-war

years has increased nearly three times as fast as the nation's (U.S. Census, 2000). Many of the newcomers to Florida came from northern areas of the United States and brought their building materials, practices and codes with them. This is why, even today, product brochures distributed in the southeastern United States from many of the largest insulation manufacturers show paper and foil-backed insulation installed with those surfaces facing the interior environment. Examples such as these can be found for both walls and ceilings. Paper (commonly used Kraft paper) and foil backing act as vapor barriers. In northern or heating-based climates this would be an appropriate installation. Both the current Florida Building Code (Florida, 2001) and the *ASHRAE Fundamentals Handbook* (American Society of Heating, Refrigeration and Air-conditioning Engineers, 1997) contain no mention of a requirement for vapor barriers in wall and ceiling cavities for Florida. Acknowledgement of moisture transport is finally being incorporated into some code documents.

Full knowledge, however, of moisture transport mechanisms in what are called hot-humid climates has not been obtained. With this in mind, a major manufacturer of numerous building materials undertook an effort to build a research facility, the Building Products Test Facility, on the University of Florida's Gainesville campus. This facility would enable researchers to investigate the long-term viability of many different products in a hot-humid climate. Initial construction began on the facility in 1996 and preliminary data were obtained in 1998. Configuration problems related to the original sensor suite were discovered and subsequently minimized with re-wiring and the addition of new sensors during 2000 and 2001. The facility has been operating since early 2001 on a continual basis.

The design phase of this facility began in 1995, before the recent emphasis on moisture transport, mold and mildew. Because of this, certain sensor choices and locations were not optimized for investigations relating to these issues. It should be stated, however, that with over 400 active sensors and its location in Florida, this facility represents the most capable research structure for building construction in the entire hot-humid region of the United States.

Due to the variety of materials and construction techniques there are numerous data streams available for research from this facility. One family of sensors produced data that were unusual and eventually led to this entire investigation. During many mornings, relative humidity sensors located in attic and cathedral ceiling spaces reported a sharp rise in relative humidity at the same time that local temperatures were increasing. These were the first indications that the facility and its sensors were picking up data related to what is now called solar induced moisture transport.

It has long been appreciated that attic ventilation can bring in (and exhaust) relatively large amounts of air and moisture through the roof venting system. In addition, some of the early research has correctly identified the moisture interactions between the attic and the conditioned spaces. In comparison, moisture transport directly across the roof envelope has not been as well studied nor understood.

The objective of this study was to use the existing facility to show that the phenomenon of solar-induced moisture transport across a shingle roof structure does exist and exhibits a significant frequency and magnitude of occurrence. This transport mechanism can be shown to exist by investigating and analyzing the following questions:

1. Is there a mechanism that produces a high moisture level or gradient at the roof line of a shingle roof structure?

2. If there is such a mechanism, how often does it occur?
3. What is the magnitude of the transport mechanism and what are the effects of actual building materials and techniques on this mechanism?
4. What, if any, effect does this moisture transport mechanism have on the long-term condition of the wood-based roof deck materials?
5. Are there any removal mechanisms for this moisture transport such that there is a negligible increase in moisture content?

The Building Products Test Facility has proven to be a valuable asset in the effort to provide answers to these and other questions relating to building products and techniques for the hot-humid regions of the United States and, in particular, the State of Florida.

This study was directed at building practices and materials common in the southeastern United States of America. Many industries in this area of the United States are international in focus and are completely comfortable with units described by the international system, or S.I. units. However, the construction trades in the U.S. and, in particular, Florida, still use the English (or inch-pound) system of units almost exclusively. Therefore, to accommodate both audiences, this study incorporates both systems of units.

CHAPTER 2
LITERATURE REVIEW

Since human beings began to seek shelter in caves, an effort has been undertaken to control the indoor environment. Whether through doorways or openings that face the ocean breeze, or early crude fireplaces that were placed inside the dwelling, the human race has worked to provide shelter that is affordable, healthy and comfortable. There are two different yet complementary approaches to meeting these goals. One is to provide mechanical, or active systems to modify the indoor climate and the other is to build shelters that exist passively within the local climate in a manner that maximizes human comfort. A brief description of some of the more significant changes that have occurred in the previous few hundred years follows.

Until fairly recently an open fire was the primary method of modifying the local environment. Whether this fire was found in an Algonquin Long House or a medieval English castle, the goal was the same, to provide an increased comfort level. In hotter climates long, narrow houses were placed perpendicular to prevailing breezes and built with openings that could take advantage of cross flow ventilation. Numerous examples of this were found throughout the southeastern United States from the time of the early settlers through the post World War II era.

One of the first efforts to apply some level of science to environmental control of buildings was provided by Benjamin Franklin. Franklin noticed that a traditional fireplace radiated heat from all sides, yet one side of the fireplace typically was exposed

to the outside environment. To solve this problem, he invented what was to become known as the Franklin Stove. This was just an early version of what is also called a pot-belly stove. This type of stove is placed in the middle of a room and radiates heat to the indoor space in all directions (Asimov, 1974). Another early inventor was Count Rumford, born Benjamin Thompson, in Woburn, Massachusetts in 1753. Since he was a Loyalist, he moved to England before the Revolutionary War. Count Rumford did early work in the study of heat. As a practical offshoot of this work, he developed a design for a more efficient fireplace. This design is known today as the Rumford Fireplace. Rumford observed that radiant heat was the primary heat transfer mechanism for fireplaces. To maximize this mode of heat transfer, his fireplace design was shallower and the inside faces were constructed to radiate more heat into the room (Asimov, 1974).

During the time of these mechanical changes, construction techniques used on common dwellings were also slowly evolving. Early crude huts gave way to stone construction. In Northern Europe and England some of thes e techniques were just a resurrection of past methods used a thousand years before by the Roman Empire. Double brick or stone wall construction provided an interstitial air gap that allowed heat and moisture to be carried up and out of the structure due to a chimney effect. Due to the enormous abundance of wood in this country, early settlers naturally made their early dwellings from locally obtained wood. The more expensive structures however were still constructed of stone and brick. As the United States developed, construction of housing moved away from the use of site materials such as fieldstone and rough-hewn logs. More and more houses were built using manufactured bricks and sawmill processed lumber. This allowed for the use of less material than earlier techniques. These changes also led

to the development of built-up walls that included interior wall cavities. Post and beam construction resulted in the use of structural beams that allowed for the placement of exterior wall coverings such as clapboard siding. At the same time the interior walls were finished with a lath-type structure coated with plaster. Moisture present in the exterior environment such as rain or excessive water vapor could bypass the exterior skin of a building through construction defects and collect in this interior space. Several things combined to mitigate any problems that this moisture could cause:

- Early construction techniques resulted in such a leaky structure that any collected moisture was just as likely to drain out of the building cavity as it was to be trapped within.
- Old growth forest products have a much tighter grain structure and were much more resistant to mold and rot due to moisture.

The development of mechanical systems followed with forced-air furnace systems and steam heating. As the 19th century passed and the 20th century began, successful work was finally accomplished in the new field called air conditioning. Early work by Gorrie and Carrier in the U.S. and Carre in France led to systems that cooled and dehumidified the indoor environment. There now existed fully developed systems to heat, cool and dehumidify the indoor environment (Donaldson and Nagengast, 1994). Fueled by cheap energy sources there was little, if any, need to develop energy efficient systems or energy efficient houses. All of this changed during the Oil Embargo of 1973.

As the real cost of energy approximately tripled in a relatively short period of time, the need for energy efficient houses, air conditioners and heating systems became apparent. At the same time, depletion of traditional building materials forced the construction industry to adopt new standards and materials of construction. Nearly thirty years have passed since this event. Many changes in the construction industry since then

have resulted in a collision of building techniques, building systems, homeowner desires and the local climate:

- Rising energy costs have caused home builders and home owners to construct and operate homes much more efficiently. Homes are built with more insulation, better windows and more efficient HVAC systems. Since one of the largest contributors to heating and cooling costs is infiltration, particular attention has been paid to this area causing infiltration rates to go from 1.0 to 1.5 air changes per hour to typically less than 0.25 air changes per hour.

- Depletion of old growth forest products (or restrictions on access to the same) has continued. New materials, while cheaper and more available, sometimes do not resist moisture driven degradation as did older materials.

- Increased efficiency of building envelopes has decreased sensible cooling loads more dramatically than latent loads. Matched equipment designs for air conditioning have become much more efficient but are designed for the average climate condition. As such, standard HVAC equipment has a more difficult time controlling humidity loads in Florida than would be the case in southern Indiana, for example.

- Many building codes were first developed for Northern climates. Vapor barrier location for cold climate construction is different than the proper location for hot-humid climates, and vapor barriers are not desirable for all types of construction in hot-humid climates.

Tighter building construction practices, brought on by a desire to minimize energy costs, coupled with changing building materials and laggard building codes have contributed to an increase in moisture related building problems. Some recent progress has been made in confronting these issues. The new Florida Building Code (Florida, 2001) deletes all references to wall and ceiling vapor barrier requirements. The only remaining requirement is between the ground and the crawl space or concrete slab. Some homebuilders and designers are recognizing that vinyl wallpaper acts as a vapor barrier in the wrong location in the hot-humid southeastern United States and are discontinuing its use. Acknowledgement of Florida's high humidity, high rainfall climate is starting to be reflected in design changes recommended by building scientists for this particular region.

Secondary drainage planes, eave size and landscaping sprinkler head location are all emerging design issues related to minimizing bulk water intrusion into the building structure.

Moisture Movement in Porous Building Products

A description of Florida's climate has been presented that characterizes Florida as hot and humid. The American Society of Heating, Refrigeration and Airconditioning Engineers (ASHRAE, 1997) defines a climate as hot and humid where one or both of the following occur:

- a 67°F (19.4°C) or higher wet bulb temperature for 3,000 or more hours during the warmest six consecutive months of the year; or
- a 73°F (22.8°C) or higher wet bulb temperature for 1,500 or more hours during the warmest six consecutive months of the year.

Another more convenient definition has been presented by Lstiburek (2000). This definition is as follows:

- A hot-humid climate is defined as a region that receives more than 20 in. (50.8 cm) of annual precipitation and where the monthly average outdoor temperature remains above 45°F (7.2°C) throughout the year.

The Florida Automated Weather Network (FAWN, 2003) operated by the University of Florida Institute of Food and Agricultural Sciences has a weather station in Alachua County. Data from this station for 2002 show a monthly average temperature between 51.7°F (10.9°C) and 77.2°F (25.1°C). Annual precipitation for the same year was approximately 48.9 in. (124.2 cm). These data are a clear indication that the local climate can be characterized as hot-humid. A North American map presented by Lstiburek (2000) describes all of Florida as being hot-humid. In addition, coastal regions of North Carolina, South Carolina, Georgia, Alabama, Mississippi, Louisiana and Texas are also defined as hot-humid. Some upland regions of these states are included as well.

The classification of Florida as being "hot-humid" comes as no surprise to everyone living in or visiting the state. The rapid increase in the use of air conditioning throughout the state and region after World War II is a testament to this classification. However, comfort is just one of the issues relating to this characterization. Decay of wood and other products can be promoted by the existence of numerous fungi that attack organic material. These organisms require three things to flourish: water, food and the proper thermal environment. Decay related to fungi occurs typically between the temperatures of 35ºF (1.7ºC) and 100ºF (37.8ºC) (*Wood Handbook*, 17-3, 17-4). Obviously many wood products in Florida residential structures are exposed to a moist environment and spend a significant portion of their life cycle within this temperature range. How moisture is stored and moves through wood products plays an integral part in understanding the behavior of moisture transport.

Early investigations of moisture transport through common organic materials came from the desire to prolong the storage life of food grains. Many products as different as wood, food grains and mineral ores need to be dried from their natural state to some specified condition. Food grains, in particular, are dried to extend storage times and limit spoilage by limiting moisture availability to decay organisms. Wood is dried both to limit decay and minimize dimensional changes after processing. Ores are dried to some point as a condition of sale. The study of drying mechanisms is probably as old as the need to dry different products (Keey, 1972). Drying methods were arrived at through trial and error methods until fairly recently.

The study of drying methods has led to increased understanding of the underlying physics that describe moisture transport in porous media. Building products that exist in

an ambient environment undergo repeated cycles of not only drying, but also wetting. This is of special concern in the hot and humid climate of Florida.

Atmospheric water vapor exerts a vapor pressure on to everything that exists within the atmosphere, including porous building products made from wood. The study of their resulting interaction can be traced back to the study of equilibrium states set forth by the Clausius-Clapeyron equation and Gibbs' ideas concerning free energy states (Keey, 1972). However, within porous materials capillary action begins to play a part. Molecules of water vapor can become trapped within the many small pores of porous materials. When this occurs, a concave meniscus will form. Keey's reference to free energy behavior shows that a convex surface requires the addition of free energy causing a rise in vapor pressure. However, the curved surface found in capillary pores causes the opposite to happen, resulting in a lowering of the vapor pressure. In this manner, water vapor in the ambient surroundings is attracted to, or adsorbed into, the porous structure of many common building materials. Since relative humidity is a measure of the degree of water vapor saturation, as the relative humidity increases, water vapor adsorption into porous materials also increases (Pedersen, 1990). Work investigating this "parallel-series" liquid and vapor flow was described in detail by Philip and de Vries (1957). A liquid island was described as a pocket of liquid water trapped in a pore. The two liquid surfaces that bound this pocket are in equilibrium with the surrounding environment. This equilibrium state is shown as the solid lines in Figure 1. If the surrounding equilibrium is modified by a vapor pressure gradient brought about by a temperature difference, vapor can be transported in the direction shown. Water condenses at surface A and evaporates at surface B causing surface A to become flatter and the surface

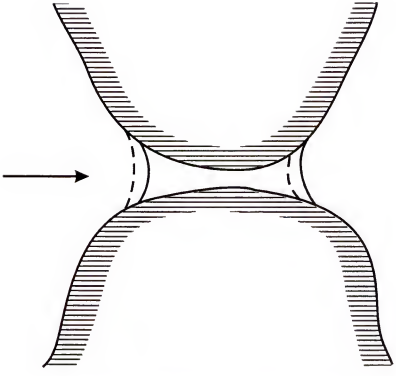

Figure 1. Water vapor transport through single pore. (Philip and de Vries, 1957)

at B to become more curved. Dashed lines in Figure 1 represent the new curves. The difference in curvature represents a difference in energy state. As long as the surface curvatures are different, vapor transport will continue. At the same time vapor is transported across air-filled pores at a rate that is governed by the vapor pressure gradient. The mass flow rate of vapor across the water pockets adjusts itself to that of the air-filled pockets.

The mechanism described allows porous materials to reach a state of equilibrium with the surrounding environment in a manner that relates ambient conditions such as relative humidity to the moisture content of the specific building material. Experimental work by several investigators has shown that the moisture content of many porous materials can be related to the relative humidity of the surrounding environment.

Ahlgren at the Lund Institute of Technology in Lund, Sweden, completed early experimental work in this area (Ahlgren, 1972). Sorption isotherms for many common building materials were constructed through experimental methods. An example of one of these isotherms from Ahlgren's work (as found in Pedersen, 1990) is shown in Figure 2. The lower curve is an adsorption line and the upper curve represents desorption. The lines that travel between the adsorption and desorption lines have been called "scanning lines" (Ahlgren). Scanning lines represent the hysteresis, or non-linear effect that occurs between drying and wetting phenomenon.

A collaborative effort between the Oak Ridge National Laboratory and the Fraunhofer Institute for Building Physics (IBP) has developed a software program that can predict heat and mass transfer in building components. A more descriptive isotherm can be found in the manual for this program (WUFI, 2000). This isotherm is shown in

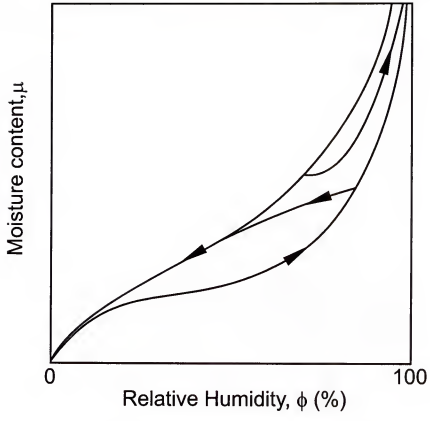

Figure 2. Wetting and drying hysteresis of porous material. (Ahlgren, 1972)

Figure 3. A detailed description of this relationship can be found in the *WUFI Manual*.

These combined efforts illustrate a methodology for measuring moisture content in wooden building products by tracking the long-term relative humidity levels in the ambient environment. Data found in the *Wood Handbook*, as cited by Sherwood (ASTM, 1994), gives recommended moisture content values for wood exposed to typical environmental conditions. Data are given for three distinct regions:

- Dry, southwestern United States
- Damp, warm coastal areas
- Remainder of continental United States

For damp, warm coastal areas exterior wood should have an average moisture content of 12%. Individual pieces should be within 9 and 14%.

While the adsorption of water vapor by porous wood products is important to the maintenance and longevity of the wood, it is equally important to investigate the transport of the water vapor itself. Another software program, MOIST (Burch and Chi, 1997), produced by the National Institute of Standards and Technology describes the transport of water vapor through building materials. The governing equation presented in the program manual is described by the conservation of mass equation for moisture distribution within a building material. The governing equation has the following form:

$$\frac{\partial}{\partial y}\left(\mu\frac{\partial p_v}{\partial y}\right)-\frac{\partial}{\partial y}\left(K\frac{\partial p_l}{\partial y}\right)=\rho_d\frac{\partial \gamma}{\partial t}, \qquad \text{Equation 1}$$

where the units for each symbol are as follows:

Symbol	S.I. units	English units	Definition
y	m	ft	Distance
μ	kg/m s Pa	perm in	Water vapor permeability

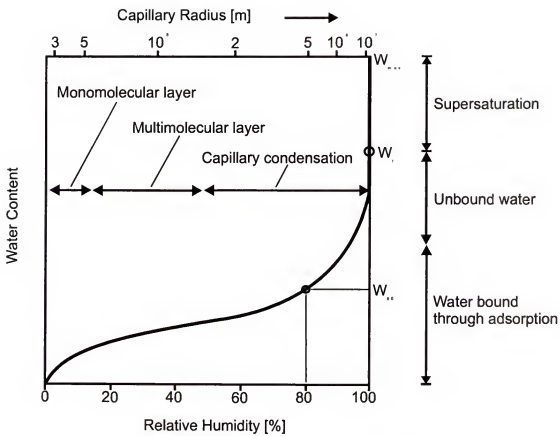

Figure 3. Relative humidity/moisture content relationship for typical building material. (*WUFI Manual*, 2000)

Symbol	S.I. units	English units	Definition
p_v	Pa	in Hg	Water vapor pressure
K	kg/m s Pa	lb/ft hr in Hg	Hydraulic conductivity
p_l	Pa	in Hg	Capillary pressure
ρ_d	kg/m^3	lb/ft^3	Dry material density
γ	kg/kg	lb/lb	Moisture content on a dry mass basis
t	s	hr	time

It should be noted that in English units, a perm has the following dimensional units:

$$\text{Perm} \equiv \text{grains/hr ft}^2\text{ in Hg}$$

where 1 pound contains 7000 grains.

The term containing the (μ) quantifies water vapor diffusion and the term with K represents capillary moisture transport. The time related term on the right hand side of the equation quantifies the moisture stored within each substance. Material property data for gypsum board and the other materials used in the construction of particular test bays are found in Table 1. Calculation of the remaining vapor transport term can proceed in a fashion as illustrated by ASHRAE Fundamentals and demonstrated by Acker (1998).

$$M = \frac{1}{\frac{1}{perm_1} + \frac{1}{perm_2} + \frac{1}{perm_3} + \ldots\ldots\ldots \frac{1}{perm_n}}, \qquad \text{Equation 2}$$

where M is the overall Perm value for the ceiling construction and ($P_{v1} - P_{v2}$) represents the water vapor pressure differential across the ceiling plane. The overall rate of water vapor transport per unit area can be calculated from:

$$W = M(P_{v1} - P_{v2}), \qquad \text{Equation 3}$$

where W has units of kg/m^2 s or lb/ft^2 hr

Table 1. Material properties

Material	Sorption Coefficients			Capillary Coefficients			Vapor Permeability Coefficients		
	A1[a]	A2[a]	A3[a]	C1[b]	C2[a]	γ[a]	B1[c]	B2[c]	B3[a]
Drywall (Gypsum board)	0.336×10^{-2}	0.100×10^{-7}	0.901	0.3054×10^{-3} (0.7881×10^{-8})	0.3883×10^{1}	0.10×10^{1}	0.4373×10^{2} (0.6381×10^{-10})	0 (0)	0
Fiberglass	0.1703×10^{-2}	0.100×10^{-7}	0.963	0 (0)	0 (0)	0 (0)	0.125×10^{3} (0.1824×10^{-9})	0 (0)	0
OSB	0.2120	0.343×10^{1}	0.811	0.3488×10^{-5} (0.9001×10^{-10})	0.38×10^{1}	0.115×10^{1}	0.4397 (0.6416×10^{-12})	0.2923×10^{-1} (0.4266×10^{-13})	0.4878×10^{1}
Building paper (Asphalt)	0.519×10^{2}	0.2538×10^{4}	0.902	0 (0)	0	0	0.35 (0.5108×10^{-12})	0 (0)	0
Roofing shingles (Asphalt)	0.519×10^{2}	0.2538×10^{4}	0.902	0 (0)	0	0	0.375×10^{-1} (05472×10^{-13})	0 (0)	0

[a] Coefficients A1, A2, A3, C2, γ and B3 are dimensionless and the magnitudes are the same in both English and SI units.
[b] C1 is expressed in (m^2/s) and ft^2/hr.
[c] B1 and B2 are expressed in (kg/s.m.Pa) and perm-inch.

Permeability data have been collected from various researchers and can be found in the material database associated with the MOIST software program. The data have been experimentally fitted to an equation of the form:

$$\mu = B_1 + B_2 e^{B_3 \phi} \qquad \text{Equation 4}$$

where μ and B_1 are in units of perm-inch (kg/s m Pa). μ in this form can be divided by the thickness of each material to obtain the Perm value that is needed for Equation 3.

From these series of equations, and with knowledge of the building materials and surrounding environment, water vapor fluxes can be quantified. Also important is the relationship between permeability and relative humidity as shown in Equation 4. The permeability of many materials does not depend on relative humidity. The permeability for these materials is described completely by coefficient B_1. However, permeabilities of some materials have a dramatic dependence upon the surrounding relative humidity. Coefficients B_2 and B_3 characterize this dependence. In addition, Equation 4 is dependent on material thickness. As will be shown in the Results section, oriented strand board (OSB) sheathing of a typical roof has many areas of reduced thickness. Wood chips often separate from the underside of the sheathing as nails are driven through to attach both the building felt and the shingles. This reduces the thickness of the OSB, thereby increasing the permeability.

Material property data found in Table 1 can also be used to evaluate capillary flows and water vapor sorption from the surrounding environment. These equations are also found in the MOIST software manual. Equation 5 relates the moisture content of a building material, γ, expressed as a fraction, to the surrounding relative humidity, ϕ, also expressed as a fraction.

$$\gamma = \frac{A1\phi}{(1 + A2\phi)(1 - A3\phi)} \qquad \text{Equation 5}$$

Capillary flows are described by Equation 6, where liquid diffusivity, D_γ and C_1, are calculated in units of m^2/s or ft^2/hr. The coefficient C_2 is dimensionless.

$$D_\gamma = C_1 e^{C_2 \gamma} \qquad \text{Equation 6}$$

Ventilation of Attic Spaces

A relationship has been introduced that allows a correlation to be made between the moisture content of wood building products and the relative humidity of the surrounding air. It has been further shown that maintenance of wood materials requires these products be kept below a maximum moisture content reported by Sherwood and others. Many areas within a residential structure are ventilated (both purposefully and unintentionally). One long-standing guideline has been to ventilate attic spaces. Both attic spaces and cathedral spaces have traditionally been ventilated. This practice, however, has come into question lately by Rose and others. Rose and TenWolde (2002) describe the history of attic construction techniques, research and evolution for the last sixty years or so. A review of the sources cited in this article quickly leads to the conclusion that the majority of the work accomplished in this area was done in cold or mixed climate regions, with little, if any, accomplished in hot-humid climates. However, some discussion of the underlying fundamentals that were presented in this earlier work might provide some insight to present day concerns.

Rowley was one of the earliest researchers involved in the investigation of water vapor transport through building materials (Rowley, 1939). Rowley explored the analogy between heat transfer and moisture transfer, both moving in the direction from high levels to low levels. Rowley also investigated the relationship between relative humidity and

moisture transport in hygroscopic materials. In this case moisture content of porous materials, such as wood, can be correlated to the surrounding ambient relative humidity. Jordan and others (Jordan, et al., 1949), in their investigation of three instrumented houses in Madison, Wisconsin, used this behavior to measure the average relative humidity in the attic spaces of these houses. Test coupons of wood were placed in the attic and periodically weighed. The change in weight was related to the relative humidity. Results from this paper showed that attic condensation could be controlled by ventilation, relative humidity in the conditioned space, and the use of vapor barriers in ceilings below attics. Again, it should be emphasized that this behavior occurred in three houses located in Madison, Wisconsin.

From these and other early investigations came the ventilation requirement for attic spaces of 1:300, or one square foot of ventilation area per 300 square feet of horizontally projected ceiling area. As Rose has pointed out, no traceability exists between this exact requirement and the early investigations. Nevertheless, national building codes have included requirements for attic ventilation for many years. Furthermore, very little work has been completed relating to ventilation requirements for attic spaces located in hot-humid climates (Rose and TenWolde, 2002). It should also be noted that the new Florida Building Code includes a ventilation requirement for roof structures that are constructed with wood. This requirement calls for one square foot of net free ventilating area for each 150 square feet of ceiling. There are some exceptions that can reduce this requirement to the familiar 1:300 ratio (Florida, 2001).

While it appears to be true that little work (if any) has been done with the purpose of promulgating building code language for attic ventilation in hot-humid climates, some

work attempted to fully describe the various moisture transport mechanisms (sources included later), especially solar induced moisture transport.

This transport mechanism is not currently well understood, especially in hot-humid climates. Briefly described, this phenomenon occurs when a surface is coated with water (from rain, dew or irrigation) and is then exposed to sunlight, causing a rise in vapor pressure of the water layer, such that the vapor is driven into the adjacent structure. This transport mechanism can happen in many different ways:

- Landscape irrigation on walls
- Rainfall on walls and roofs
- Condensation on walls and roofs

This last mechanism is of primary importance due to its frequency of occurrence and relationship with attic ventilation. Liquid water on the roof does not, by itself, cause moisture transport problems. The entire sequence of events can more properly be described as having the following steps:

- There must be a source of water, in this case from nighttime cooling and subsequent formation of condensation.
- Pathways must be present. The typical shingle roof is not a vapor barrier. Various pathways will be described.
- A driving force must be present.

A graphical representation of the solar-induced transport mechanism is shown in Figure 4. This proposed model begins with nighttime radiant cooling of the roof shingles and underlying structure. If the shingle temperature goes below the ambient dewpoint, condensation will form on the surface of the shingles. When the sun rises, solar radiation heats the water layer covering the dark shingled roof and rapidly heats the water above the temperature of the surrounding air. The resulting vapor pressure is much higher than

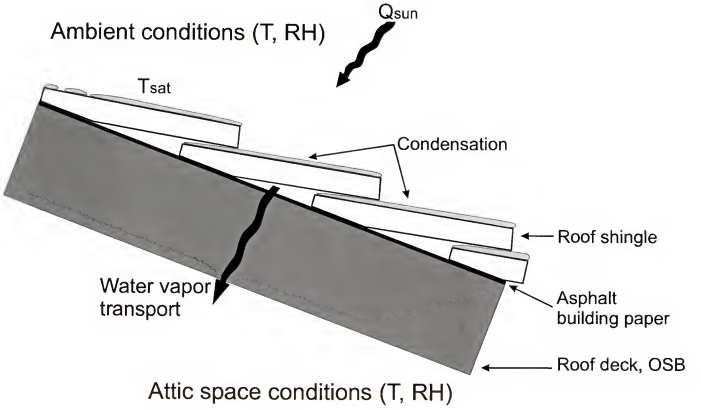

Figure 4 Solar-induced moisture transport across a shingle roof boundary.

the vapor pressure in the attic space. This difference drives the moisture across the roof boundary and into the attic.

Some work relating directly to this phenomenon has been done by Cunningham in New Zealand. After being made aware of moisture problems in local cathedral style roof structures, an experimental study was undertaken to investigate solar induced moisture transport phenomenon across the roof/interior boundary. Three key points are made in this investigation:

1. The climatological location of this study could be described as temperate or mixed, not hot and humid. While the phenomenon is of critical interest, the differences in climate make any comparisons general, rather than specific.

2. A comment about construction type and its effect on the process should be quoted directly:

> It should be noted that problems with moisture transfer under investigation here have been noted only in "cathedral"-type ceilings. These have relatively airtight roof cavities. No problems have been noted with absorbent roofing materials conventionally installed in hip-type roofs with an attic space. Apparently, any moisture that does transfer through the roof into an attic space has ample opportunity to disperse by natural ventilation. (Cunningham, et al., 1990)

3. The experimental apparatus showed that moisture could be driven across a roof boundary under simulated solar heating.

An additional paper by Cunningham (1994) stresses the need for experimental and field study verification of the process of solar-induced moisture transport. As Cunningham states, the need for verification of this process is driven by the complexity of the problem. He lists the most significant ones:

- Laboratory tests are small and can only approximate as-built structures
- Night sky radiant cooling is difficult to simulate in the laboratory
- Cross-ventilation is difficult to simulate in the laboratory
- Occupant behavior can also be difficult to simulate

Existing literature can provide guidelines and descriptions of attic and cathedral space ventilations for cold climates. Additional details can be found describing solar-induced moisture flows in temperate climate simulations. As Rose has pointed out, there has not been enough research done to support a recommendation for ventilation of attic spaces in hot-humid climates. The very nature of this claim could be used to also state that construction of non-vented attic spaces in hot-humid climates cannot be supported either.

By having the Building Products Test Facility constructed in a hot-humid climate, this lack of research can be addressed. This facility was not constructed specifically to investigate this area of building science or solar induced moisture transport. Due to the limited amount of research conducted in this area, this is not surprising. Because of this, sensor location and type is not necessarily optimized to investigate these phenomena. However, it was felt that data existed for the objective to be investigated and analyzed.

CHAPTER 3
METHODS AND EQUIPMENT

This research dealt with the effects of moisture vapor transport in cathedral and attic spaces of residential structures. A test facility was constructed that would allow study of this and other phenomena related to building construction techniques in hot-humid climates.

Building Products Test Facility

A test facility was constructed using materials and techniques typically found in residential and light commercial construction projects located in the coastal region of the Southeastern United States. This area would include all of Florida and the coastal regions of Texas, Louisiana, Mississippi, Alabama, Georgia and North and South Carolina. Construction began in late 1996 and was completed in 1997. The facility is located in Gainesville, Florida with latitude and longitude of 29.2° N and 81.2° W, respectively. The building was designed and constructed in a modular fashion to facilitate future structural modifications. To reduce end effects, the east and west faces of the building are used as equipment and storage bays, and as such, are not instrumented. The west end bay contains all of the data acquisition and control equipment. The east end bay is used for storage. A plan view of the building is shown in Figure 5. An exterior view of the building (from the south side) is included as Figure 6.

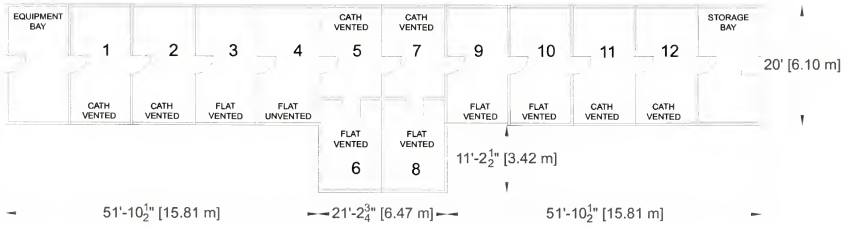

Figure 5. Plan view: Building Products Test Facility

Figure 6. Building Products Test Facility: southern exposure.

Building layout

While each test bay is unique with regard to certain features, there are some common construction details throughout the facility. The exterior surface of the building is covered with vinyl siding. Underneath this material is standard weight roofing felt attached to oriented strand board (OSB) with plastic-headed roofing felt nails. The OSB is nominally 0.5 in. (12.7 mm) thick. Beneath this layer significant differences begin to appear. The western half of the building is framed with light gauge steel framing members and rests on a slab-on-grade concrete foundation. The wall cross-section is based on a typical 2 × 4 dimension. Since a typical 2 × 4 does not have dimensions of 2 inches by 4 inches, its use in this document is a as a naming convention. For comparison purposes a 2 × 4 is actually 1.5 in. by 3.5 in. or 38 mm by 89 mm. The eastern half of the building is framed with wood framing members, also based on a typical 2 × 4 dimension, and the last four bays are built over individual crawl spaces. Each crawl space is separated from the adjacent crawl space and the ground is covered with a continuous vapor barrier. Each bay is insulated in a particular pattern with a combination of insulation products. The different insulation types and locations are described in the following section.

Insulation Materials and Locations

There are six different insulation types or materials used in this facility. In addition, each test bay has a unique insulation schedule. The different materials used are:

- **R-15 Batts:** Industry practice describes the insulation value in terms of the inverse of the conductance. R-15 is therefore equivalent to 0.067 BTU/hr ft2 °F (0.38 W/m2 °K). This batt style will fit in a typical 2 × 4 wall cavity. The insulation material is fiber glass that has been attached to a Kraft paper backing. The R-15 batts are used for the equipment and storage bay walls and all partition walls.

- **R-30 Batts**: These batts are twice as thick as the R-15 batts. The overall conductance value of this insulation is 0.033 BTU/hr ft2 °F (0.19 W/m2 °K). The insulation material is fiberglass and it is also attached to a Kraft paper backing. This thicker insulation is typically used in cathedral ceiling spaces.

- **Blown-in-Blanket System (BIBS)**: Wall cavities can be more efficiently filled using this material. A thin nylon mesh is attached to the inside surface of the wall framing members. Fiber glass tufts are blown into the wall cavity through a small slit in the mesh. This same method can be used in attic spaces without the need for the mesh. Typically a small amount of adhesive is mixed with the insulation when it is blown into place. Once the insulation dries it is held into place and is less likely to be disturbed by settling in wall cavities or by air currents in the attic.

- **Spray Stabilized Cellulose**: In a similar manner to the BIBS, recycled newsprint is shredded, treated with fire retardants and adhesives and blown into building spaces as insulation material.

- **Loose Fill Cellulose**: Loose cellulose is also used in attic spaces.

- **R-25 Encapsulated Batts**: The floors of bays that are constructed with crawl spaces are insulated with R-25 encapsulated batts. These batts are formulated to reduce exposed fibers.

All test bay walls are insulated to a value of R-15 and all attic and cathedral spaces are insulated to a value of R-30. Table 2 lists the type of insulation and location for each test bay in the facility. Table 3 describes the placement of the vapor barrier in the walls of each test bay. The vapor barrier is a standard polyethylene plastic sheet, approximately 0.003 in. (0.08 mm) thick. The interior walls were finished with paper-backed gypsum board that is nominally 0.5 in. thick, installed at 15/32 in. thick (12mm), and were drywall taped and spackled to provide for a smooth sealed painting surface. The interior walls were painted with a white interior acrylic latex paint.

Table 2. Test bay insulation schedule

Bay	Location	Insulation
1	North wall	BIBS
	South wall	BIBS
	North ceiling	R-30 cathedral batts
	South ceiling	R-30 BIBS
2	North wall	BIBS
	South wall	BIBS
	North ceiling	R-30 BIBS
	South ceiling	R-30 cathedral batts
3	North wall	Spray stabilized cellulose
	South wall	Spray stabilized cellulose
	North ceiling	R-30 spray stabilized cellulose
	South ceiling	R-30 BIBS
4	North wall	Spray stabilized cellulose
	South wall	Spray stabilized cellulose
	North ceiling	R-30 BIBS
	South ceiling	R-30 loose fill cellulose
5	North wall	BIBS
	South wall	N/A
	East ceiling	R-30 BIBS
	West ceiling	R-30 cathedral batts
6	North wall	BIBS
	South wall	BIBS
	Ceiling	R-30 batts
7	North wall	BIBS
	South wall	N/A
	East ceiling	R-30 BIBS
	West ceiling	R-30 cathedral batts
8	North wall	N/A
	South wall	R-30 BIBS
	Ceiling	R-30 batts

Table 2. Continued

Bay	Location	Insulatio
9	Floor	R-25 encapsulated batts
	North wall	Spray stabilized cellulose
	South wall	Spray stabilized cellulose
	North ceiling	R-30 BIBS
	South ceiling	R-30 loose fill cellulose
10	Floor	R-25 encapsulated batts
	North wall	Spray stabilized cellulose
	South wall	Spray stabilized cellulose
	North ceiling	R-30 spray stabilized cellulose
	South ceiling	R-30 BIBS
11	Floor	R-25 encapsulated batts
	North wall	BIBS
	South wall	BIBS
	North ceiling	R-30 BIBS
	South ceiling	R-30 cathedral batts
12	Floor	R-25 encapsulated batts
	North wall	BIBS
	South wall	BIBS
	North ceiling	R-30 cathedral batts
	South ceiling	R-30 BIBS

Table 3. Test bay vapor retarder schedule

Bay	Location
1	North wall: vapor barrier outside OSB
	South wall: vapor barrier outside OSB
2	North wall: vapor barrier inside cavity next to dry wall
	South wall: vapor barrier inside cavity next to dry wall
3	North wall: vapor barrier inside cavity next to dry wall
	South wall: vapor barrier inside cavity next to dry wall
4	North wall: no vapor barrier
	South wall: no vapor barrier
5	North wall: no vapor barrier
	South wall: N/A
6	North wall: N/A
	South wall: no vapor barrier
7	North wall: no vapor barrier
	South wall: N/A
8	North wall: N/A
	South wall: no vapor barrier
9	North wall: no vapor barrier
	South wall: no vapor barrier
10	North wall: vapor barrier inside cavity next to dry wall
	South wall: vapor barrier inside cavity next to dry wall
11	North wall: vapor barrier inside cavity next to dry wall
	South wall: vapor barrier inside cavity next to dry wall
12	North wall: vapor barrier outside OSB
	South wall: vapor barrier outside OSB

Individual Test Bay Description

The interior of the test bays can be broken down into six categories. A brief description of the test bay interiors follows.

Test Bays 1 and 2 are built on a slab floor and foundation and have cathedral ceilings. The walls and roof are framed with steel framing members.

Test Bays 3 and 4 are built on a slab floor and foundation and have a typical attic space above the test bay interior. The walls and roof are framed with steel framing members.

Test Bays 5 and 7 have north-facing roofs, cathedral ceilings and are built on a slab floor and foundation. The walls and roof of Bay 5 are framed with steel framing members. Test Bay 7 is framed with wood framing members.

Test Bays 6 and 8 are directly opposite of Bays 5 and 7 and are also built on a slab floor and foundation. These bays have attic spaces and south-facing roofs. The walls and roof are of Bay 6 are framed with steel framing members. Test Bay 8 is framed with wood framing members.

Test Bays 9 and 10 are built with a wood floor over a vented crawl space. These bays have an attic space and are framed with wood framing members.

Test Bays 11 and 12 are built with a wood floor over a vented crawl space. These bays have cathedral ceilings and are framed with wood framing members.

Test Bay 2 Description

Test Bay 2 is built with a rectangular floor plan. The bay interior is 119.9 in. (3045 mm) wide and 230 in. (5842 mm) long. The peak of the cathedral ceiling is 147.5 in. (3747 mm) above the concrete slab floor. The interior height of the exterior walls is 94.1 in. (2391 mm) from the slab to the ceiling line. The total interior volume of the test

bay is 1936 ft^3 (54.8 m^3). Test Bay 2 is equipped with numerous sensors located throughout the test bay. A short description of each sensor type is included in this chapter and additional data are located in the appendix.

Sensor descriptions

Thermocouples: Pre-made thermocouple assemblies were purchased from Omega Engineering, Inc. Type T (copper/constantan) thermocouple assemblies were chosen and special limits of error wire was specified. Type T was chosen because of its suitability for low temperature applications in the presence of moisture. The wire gage of these assemblies is 24 AWG and the lead lengths are 36 in. (914 mm). The wires are insulated with glass braid. The full part number for this assembly is 5TC-GG-T-24-36-SMP-M. The last group of letters indicates that the assembly was ordered with a male type sub-miniature connector attached. Additional detail is included in Appendix A.

Temperature/Relative Humidity Sensors: A combination temperature and relative humidity (T/RH) sensor is used throughout the test facility. Due to accuracy and ruggedness requirements, the Vaisala, Inc. T/RH sensor was chosen. Model HMD 60Y measures both temperature and relative humidity and has a 4-20 mA output signal for each. The duct mount version of this sensor allows placement on the wall while measuring the temperature and relative humidity approximately 1.0 foot (304.8 mm) away from the wall boundary layer. The accuracy of the RH measurement is +/- 2% at 20°C. Figure 7 is a close-up of a HMD60Y T/RH sensor. Additional data are included in Appendix A.

Velocity/Temperature Sensors: All test bays were originally constructed with vented attic spaces. Continuous soffit and ridge vents are located along the entire length of each test bay eave and roof ridge, respectively. Test Bays 1 through 4 are equipped

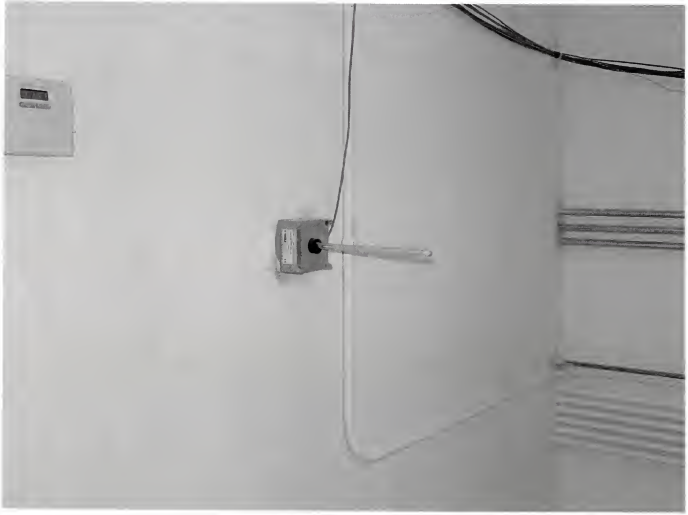

Figure 7. Typical test bay temperature/relative humidity sensor placement.

with attic and cathedral ceiling airflow sensors. These sensors are based on the hot-wire anemometer principle and therefore also include temperature sensors. Cathedral ceilings located in Bays 1 and 2 have a central ridge beam that divides the ridge vent area. These spaces are equipped with two sensors at the ridge (one on the north side and one on the south side) and one at each soffit. The flat ceiling attic spaces have one sensor at the ridge and one each at the north and south soffits. See Figures 8 and 9 for additional details. Ebtron, Inc. manufactured the airflow sensors and these particular models have a velocity range of 0 to 100 feet per minute (0 – 0.51 m/s) and a temperature range of 0 to 200ºF (-17.8ºC to 93.3ºC). The temperature output signal is 0 – 5VDC and the velocity output signal is 4-20 mA. Additional details of this sensor are included in Appendix A.

Humidity Ratio Sensors: Due to the cost of the individual Vaisala T/RH sensors, researchers at the University of Minnesota manufactured an additional set of T/RH sensors. To distinguish these sensors from the Vaisala type, they have been labeled HR sensors in the data acquisition system. They are referred to as HR sensors for the remainder of the study. Since data from these sensors was not used for this research, and the construction and use of these sensors are proprietary, no further discussion or description of these sensors has been included.

KW/KWH Transducers: Each test bay is equipped with a packaged-through-the-wall air conditioner. Heat strips that were factory installed in the air conditioning (AC) units provide winter heating. Energy consumption during both the heating and cooling seasons is measured with a Veris Industries H-6000 Series KW/KWH Transducer. Each test bay is equipped with a wall-mounted version of these sensors. The output signal can either be a pulsed signal related to discrete units of energy or a continuous 4-20 mA signal. Due to noise considerations with the data acquisition system

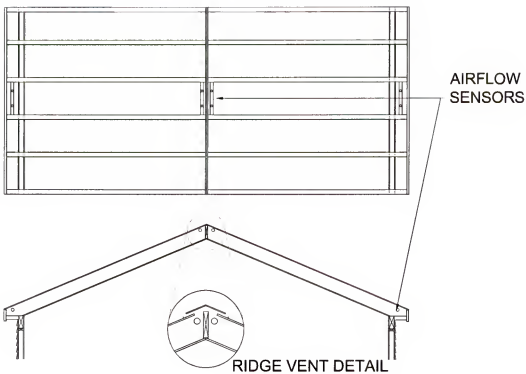

Figure 8. Location of cathedral ceiling airflow sensors

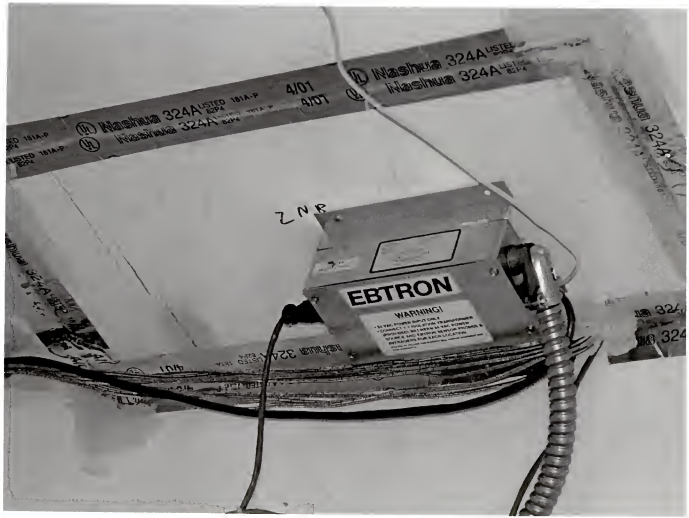

Figure 9. Cathedral ceiling airflow sensors: interior instrumentation package.

the 4-20 mA output signal was chosen for this application. Further details of this sensor are also located in Appendix A.

Sensor location

The sensor families described in the previous section are located in the following general areas at the Test Facility:

- **Roof:** Thermocouples are located above the roof sheathing but below the shingles and roofing felt. These thermocouples are labeled as sub-shingle. Other thermocouples (mostly in bays with attic spaces) are located on the under side of the roof sheathing.

- **Attic:** Attic spaces include both cathedral ceilings and the space above flat ceilings. In cathedral ceilings, such as Bay 2, a set of thermocouples is located within the roof insulation. In flat ceilings, this same set of thermocouples is located above the floor of the attic. Computer-aided-drafting (CAD) drawings and photographs illustrate the location and installation of both roof and attic thermocouples in Figures 10 and 11. Attic spaces also contain selected temperature/relative humidity sensors. These are located in Bays 2, 3, 4, 6, 8, 9, 10 and 11. The first four bays also contain air-flow sensors that measure convection and pressure driven air velocities in the attic spaces. The air-flow and T/RH sensors have been described previously.

- **Walls:** The original set of wall thermocouples is located as shown in the CAD drawings in Figures 12 and 13. To provide further detail, additional wall thermocouples were installed in the locations shown in Figure 14. These provide a more detailed thermal gradient picture, both vertically and horizontally.

Weather Station

The test facility is equipped with a standard weather station, packaged and delivered by Campbell Scientific, Inc. The weather station is located approximately 60 feet from the northwest corner of the Test Facility. Property constraints did not allow for a wider spacing. The weather station includes the following equipment and sensor package:

- **Tower:** A ten-foot open structure tower with adjustable mast is attached to a buried concrete base for stability. The instrumentation and power lines run through a sealed PVC pipe from the junction box through the concrete base and back to the test facility.

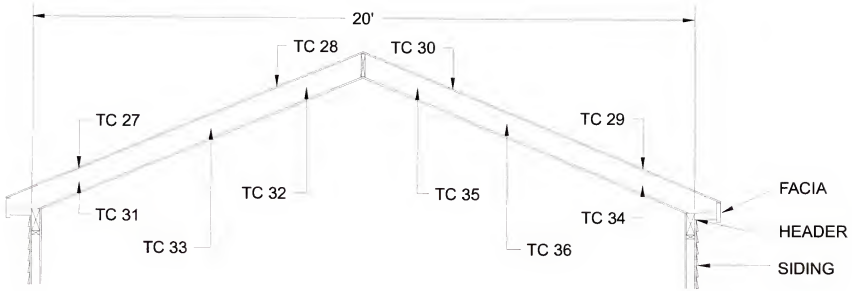

Figure 10. Typical cathedral ceiling thermocouple (TC) placement.

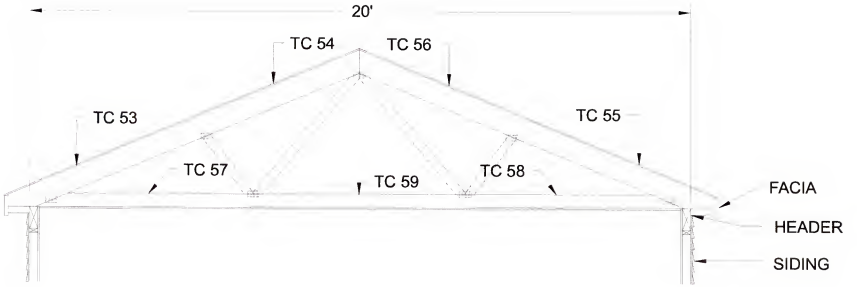

Figure 11. Typical attic space thermocouple (TC) placement

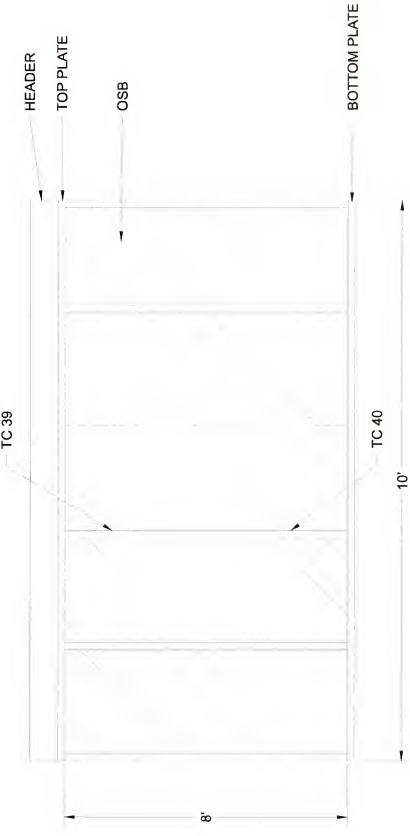

Figure 12. Original wall thermocouple (TC) placement: south wall, Bay 2.

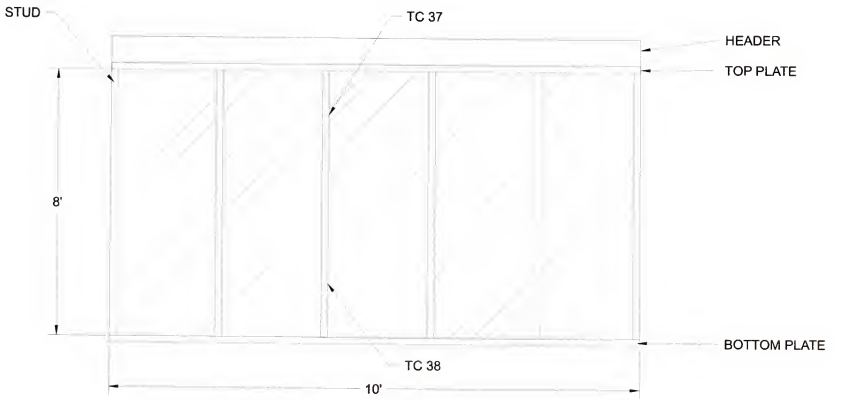

Figure 13. Original wall thermocouple (TC) placement: north wall, Bay 2.

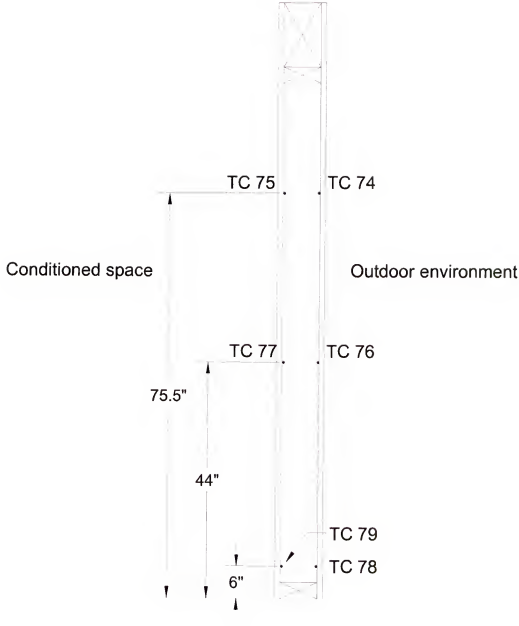

Figure 14. Upgraded wall sensors: additional thermocouples (TC).

- **Temperature and Relative Humidity Sensor:** A Vaisala T/RH sensor is installed in a solar radiation shield. This sensor measures both ambient temperature and ambient relative humidity. The original sensor was struck by lightning in the summer of 1999 and replaced with a Vaisala T/RH model identical to the ones installed in the test bays.

- **Pyranometer:** Incident solar radiation is measured using a LiCor LI200X pyranometer. This pyranometer has been calibrated for the visible, or natural light, spectrum. Additional details for this sensor are located in Appendix A.

- **Wind Monitor:** A wind monitor, consisting of an anemometer and a weather vane, manufactured by R.M. Young, is attached to a cross arm structure that allows the sensor to be above all of the tower structure except the lightning arrestor. Additional details for this sensor are located in Appendix A.

- **Barometric Pressure:** A barometric pressure sensor is mounted in the test facility equipment bay. This sensor measures the atmospheric pressure from 800 to 1060 hecta-Pascals. The sensor is a Vaisala model PTB100A. Additional details for this sensor are located in Appendix A.

Due to numerous lightning strikes throughout this facility's operational life, only a limited subset of the information from these sensors will be used. These are the temperature and relative humidity sensor and the barometric pressure sensor.

Wiring Description

Each sensor in the Test Facility produces a signal that relates to the environment being measured. This signal must be transported to the data acquisition system for conversion and storage. This section will describe the Test Facility wiring harness from the sensor to the data acquisition equipment.

Thermocouple wiring

The majority of the sensors in this facility are thermocouples. There are a total of 288 thermocouples installed throughout the facility. The individual thermocouple assemblies were described previously. The wiring harness begins with a female type sub-miniature connector that mates with the sensor assembly. This connector is attached to UL-Listed Type T thermocouple extension wire, part number, EXPP-T-20-UL. The

extension wire for each thermocouple is terminated within a standard 15-inch galvanized steel junction box. These boxes are attached to partition walls in each bay. Type T thermocouple terminal strips are attached to the back wall of the junction boxes. All of the thermocouples associated with a particular bay are terminated to one side of the terminal strips. The original thermocouples installed during construction of the facility were equipped with a stainless steel braided covering.

The signals from each thermocouple are brought back to the equipment bay via multi-pair extension cables. Bay 2, for example is equipped with a 16-channel extension cable and a 12-channel extension cable. A cable tray that traverses each bay from partition wall to partition wall carries all of the multi-pair cables from each bay. These details are shown in Figure 15. The extension cable was specified for special limits of error for higher accuracy. Additional details of the extension cable and the multi-pair cables are included in Appendix A.

Signal wiring

Each test bay has a unique set of sensors. Therefore, each bay has a unique signal-wiring layout. The specific layout for test Bay 2 is described in this section and can also be used as a general guide for the remaining 11 test bays.

The attic airflow sensors produce two separate signals, one for temperature and one for flow rate. This sensor is powered from a 24VAC power line. Alternating current (AC) power lines will be discussed in detail in the Controls section. However, as a matter of design, all AC lines are located on the north walls of each test bay and all direct current (DC) power lines are located on the south wall of each test bay.

The T/RH sensors require 18VDC and the HR sensors require 5VDC. Both of these power lines (and associated ground lines) are run in metal conduit along the south

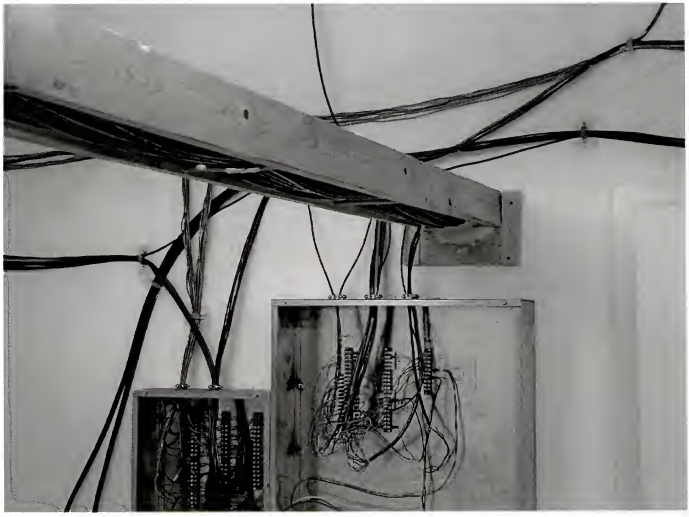

Figure 15. Bay 2 cable tray and junction box details.

wall. Since both the airflow and T/RH sensors require 3 wires, a four-wire signal cable was used for each. The unused signal wire was stubbed off at each end. Typically, a Belden-M 9512 instrumentation cable was used. This is a shielded UL listed cable with a PVC jacket and PVC insulation and four separate 22-gauge signal wires. Some of the bays use a similar cable with 24-gauge signal wires. These cables bring the signals back to a junction box in each bay.

The HR sensors are located along the exterior walls of each bay. There are a maximum of three sensors on each wall, low, middle and high. Each sensor requires a signal wire, a ground and a power line. The wire length for these sensors is relatively short and the power requirements low. These characteristics allowed the use of Category 5, or Cat5 cable, which is more commonly used for computer networking tasks. One Cat5 cable was run to each wall. This cable supplied three signal wires, a common ground, and a common power line for up to three sensors on each wall.

The last line set that was run in each bay belongs to the power meter. A single-pair shielded cable was run from the meter to the junction box in each bay. This cable carries the 4-20 mA signal that the meter produces, back to the data acquisition system.

The sensor signals (non thermocouple) in each bay are sent from the junction box to the data acquisition system via a multi-pair cable that is located in the cable tray. A nine pair Belden instrumentation and computer cable is used for this function. The signal wires are 22-gauge and PVC insulated. The nine-pair bundle is shielded and has a PVC jacket. The Belden part number is Belden-M 9309.

In a similar manner, all of the sensor signals produced in each test bay are carried back to the equipment bay at the western end of the facility.

Data Acquisition System

All of the data acquisition equipment and sensor power supplies are located in the Equipment Bay, at the western end of the test facility. This was done to eliminate the heat dissipation effects that the equipment would create if it were located in one of the test bays. The raw signals from all of the sensors are carried in over 35 multi-pair cables that are located in the cable tray. The majority of these cables carry thermocouple signals and these wires connect to specialized terminal blocks for thermocouples. All of the signal conditioning in this test facility is accomplished through the use of National Instruments Corporation SCXI hardware. National Instruments Corporation also provides an extensive suite of software to aid in the use of their products. Due to the specialized nature of this project, application specific software was produced. This software was written in Visual Basic and a copy of the data acquisition software is included in Appendix B along with additional details concerning the hardware.

Thermocouple signal conditioning

Individual thermocouple pairs are terminated to a male-type subminiature connector. This connector, in turn is mated to a corresponding terminal block channel that is numbered from 0 to 31. The thermocouple terminal block is manufactured by National Instruments of Austin, Texas and has a part number of TC 2095. These terminal blocks provide a convenient method of termination for the hundreds of thermocouples that are contained in this facility. There are nine TC 2095 terminal blocks in the rack-mount cabinet shown in Figure 16. Each TC 2095 is equipped with a thermistor for accurate cold-junction compensation and also has the capability to detect open thermocouples. A specialized 96-pin DIN connector carries the resulting signal to a corresponding 32-channel multiplexer, part number, SCXI 1100. Each channel of the

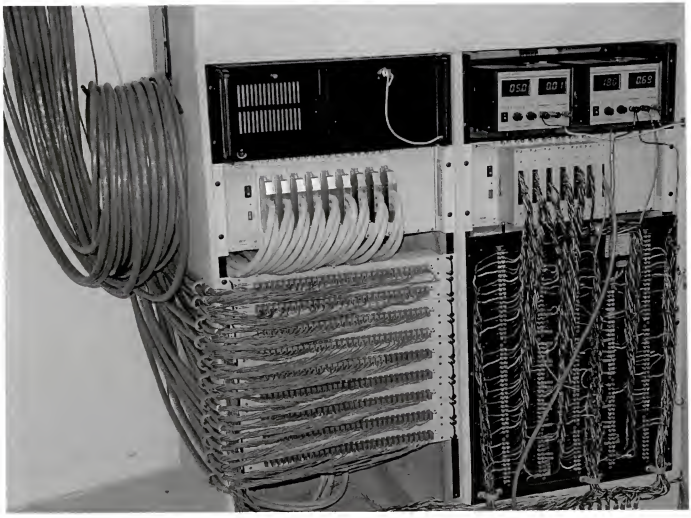

Figure 16. Data acquisition cabinet: thermocouple terminal blocks

multiplexer is configured to measure floating differential voltages with a noise filter engaged and the voltage amplifier gain set to 1000. This multiplexer also provides voltage protection circuitry up to +/- 25 Volts when the unit is powered and +/- 15 Volts when the unit is off. Each module multiplexes the 32 channels into a single channel of data for the data acquisition system. There are nine of these modules in the data acquisition system and they are plugged into a corresponding National Instruments SCXI 1001 Mainframe chassis. A single ribbon cable connects the chassis to the data acquisition card in the rack-mounted personal computer. All of these components are illustrated in Figure 16.

Voltage signal conditioning

All of the remaining voltage based signals are sent to a separate SCXI 1001 chassis. This chassis is equipped with seven 1300 family multiplexers, all manufactured by National Instruments. Six of the mutiplexers are general-purpose 1300 and 1303 modules. Each of these modules are configured to measure ground referenced voltages with a 100 Hz filter engaged and the voltage amplifier gain set to unity. In the case where a 4-20 mA signal was present (i.e. the Vaisala T/RH sensors), a National Instruments 249 ohm precision resistor was installed to provide a 1 to 5 VDC output signal.

The weather station's signals are conditioned with a single SCXI 1322 multiplexer. Each channel has its own filter and gain settings. As in the other modules, any 4-20 mA signal is converted to a 1 to 5 VDC signal with a 249 ohm precision resistor. The voltage side of the data acquisition cabinet is shown in Figure 17.

Each SCXI 1001 chassis is daisy chained through a ribbon cable to a single National Instruments MIO16XE50 16 bit analog to digital converter.

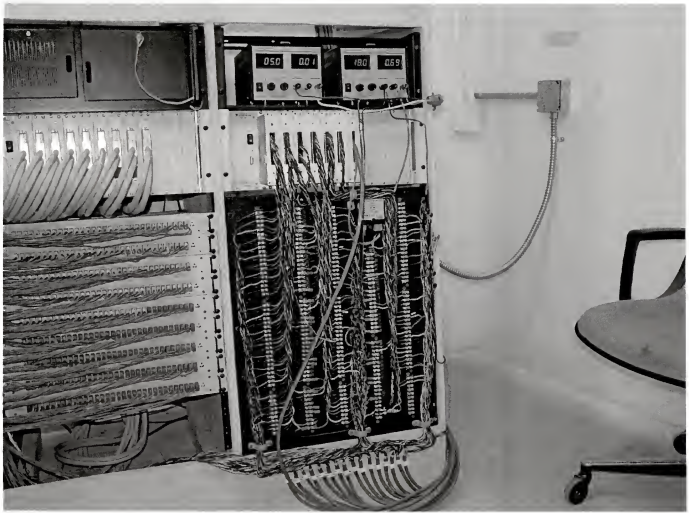

Figure 17. Data acquisition cabinet: voltage signal terminations.

The use of the National Instruments thermocouple terminal blocks (TC 2095) allows for the direct calculation of temperatures within the data acquisition system. All other signals are still in milliamp or voltage form. The final form of the data is produced within an SQL database that resides on a separate server connected to the test facility via a fiber optic data link.

The data acquisition software produces data streams that are inputs to the SQL software. The entire data acquisition code is included in the appendix. Within the code are stored procedures such as: sql = stp_Ins_Data. This procedure looks for three inputs:

- A unique date and time stamp
- The sensor identification description
- The data unique to the time and sensor

Once the data for each time stamp has been placed in the data table, additional manipulation can occur. The data table is joined to the sensor definition table. A diagram of this process is shown in Figure 18. The sensor definition table contains all of the scaling factors that turn the data signals into physical measurements. Scaling the data with the SQL program provides for long-term data acquisition flexibility within the test facility. Individual sensors can be replaced or modified without the requirement to change the client, or data acquisition software. All that needs to be changed is a single line of code within the sensor definition table.

The output of the SQL program consists of three tables:

- Thermocouple Data table
- Voltage Data table
- Weather Data table

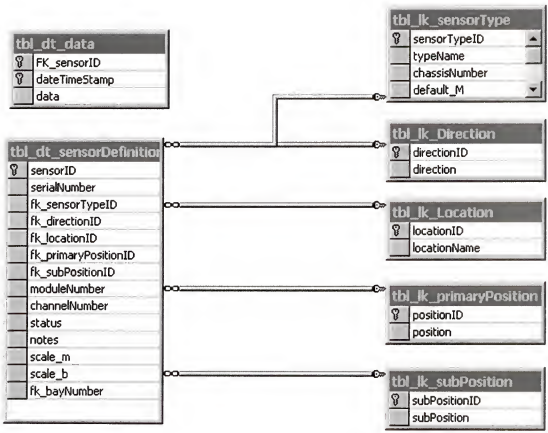

Figure 18. SQL process diagram

Near real time viewing of these data is made possible through the use of another unique piece of software designed for this facility. To provide for data security, viewing of the data was made possible through user-friendly programming written in Visual Basic. Loading the software on individual computers allows the user to connect to the server and download data through a field-selectable program screen. A screen shot of the Visual Basic programd is shown in Figure 19. Data can be selected by:

- A date or date period
- Individual test bays
- Unique sensors

Once selected, the data can be exported to an Excel spreadsheet, which allows for rapid preview of particular data streams of interest.

Environmental Control System

The Building Test Facility was designed to incorporate an environmental control system for each test bay. Each bay can have individual set points for both temperature and relative humidity. Typically, all of the bays have common set points, which provides for more effective comparisons. During 2001 and 2002, the temperature set point was fixed at 76F (24.4C) and three different cases were investigated for relative humidity:

- All bays were set at 60% RH for two weeks in the summer of 2001
- All bays were set at 50% RH for two weeks in the summer of 2001
- Relative humidity was naturally controlled by air conditioner operation during the remainder of this test period.

Control system design and operation

The control system is a separate data acquisition system equipped with modules manufactured by National Instruments. A picture of the control system is shown in

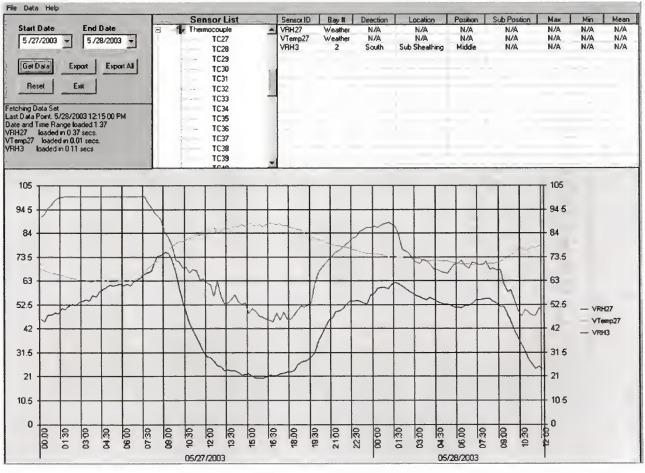

Figure 19. Visual Basic data viewer.

Figure 20. This system is similar to the one previously described, only smaller. The main chassis is an SCXI 1000 model, which is a four-slot chassis. The control system uses four signal conditioning modules; two for input and two for output. The input control modules are National Instruments SCXI 1300 modules and the output modules are National Instruments SCXI 1326 High Voltage modules.

Inputs come from previously described T/RH sensors mounted in the conditioned space of each test bay. Due to the unique characteristics of the T/RH sensors, the signals from these sensors can be split into two data streams: one for the other data acquisition cabinet and one for the control system. In this manner the bay environmental conditions can be transmitted to the control system in addition to be used for archival purposes. The control system software (included in Appendix C) scales the temperature and relative humidity data so the operator can input engineering values rather than millivolt and milliamp signals. An environmental control and viewer screen was designed to allow for real-time system diagnostics and manipulation of individual setpoints. The screen, shown in Figure 21, represents the start-up period where the bay temperatures have not yet reached the control setpoint.

The software was designed to minimize control overshoot within the mechanical restrictions of the heating and cooling equipment. The air conditioning compressor was originally equipped with a 240-second delay that prevented rapid restart during momentary power outages. Since the control system bypassed all internal electro-mechanical controls, this same delay was incorporated into the control software and precluded the use of a more detailed control scheme. In addition a software deadband was incorporated to prevent the requirement for simultaneous heating and cooling. For example, if the temperature setpoint is 76°F (24.4°C), the air conditioner will come on

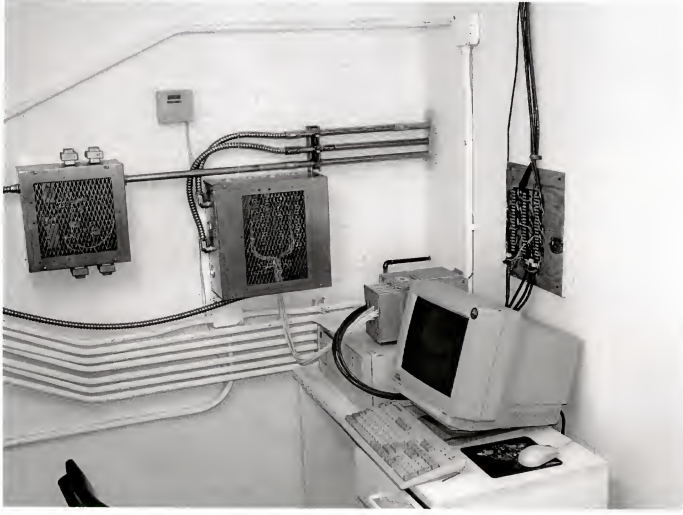

Figure 20. Environmental control system

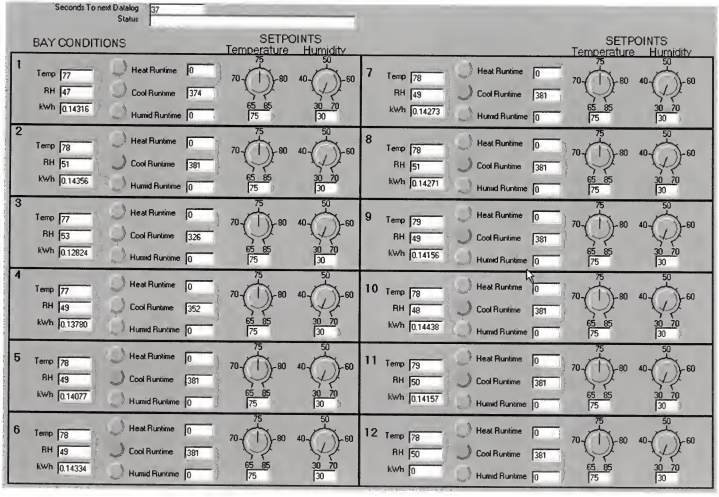

Figure 21. Environmental control system data viewer.

at temperatures greater than 77°F (25°C) and the heat will come on at temperatures less than 75°F (23.9°C). The resultant simple control strategy provides fairly accurate long-term control of test bay conditions. Figure 22 shows a 48-hour summer period for Bay 2 conditions and Figure 23 shows a 48-hour winter period.

The use of the SCXI 1326 High Voltage modules allows the controls to be switched directly from the 24VAC system. Since this is a standard voltage for AC controls, the entire system is simplified. Each bay is equipped with three separate control lines; one each for air conditioning, heating and humidification. The air conditioner is a small through-the-wall unit manufactured by General Electric with 8500 BTU/hr (2490 Watts) capacity. The air conditioners are installed on the north wall of each bay, with the exception of Bays 6 and 8, which are on the west and east walls, respectively. The air conditioner is also equipped with heat strips for space heating purposes. Additional details for the air conditioner are included in Appendix D. The control panels on each unit have been bypassed and the controls moved to individual junction boxes in each bay. The relays in the junction box control the heat strips and air conditioner. The fan is activated by a demand for either heating or cooling.

A simplified humidity control system was implemented for the Test Facility. Funding constraints did not allow for a simultaneous control strategy for both cooling and humidity control. The installed system allowed for the addition of water vapor independent from the cooling system. The same time delay counter used for the air conditioner was also incorporated into the humidity control system. This delay prevented the over-application of humidity.

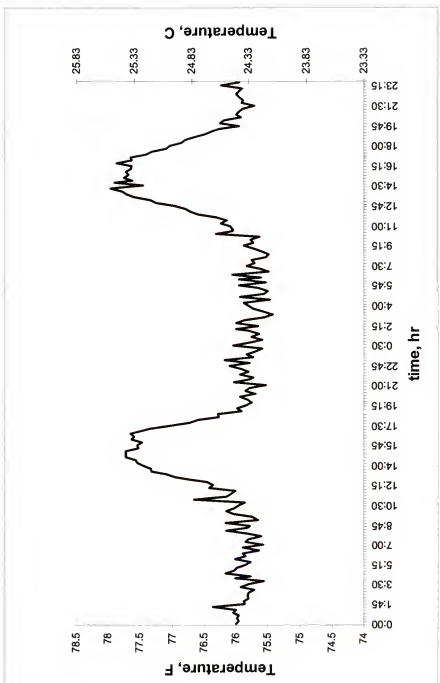

Figure 22. Bay 2 summer period temperature control history (48 hrs).

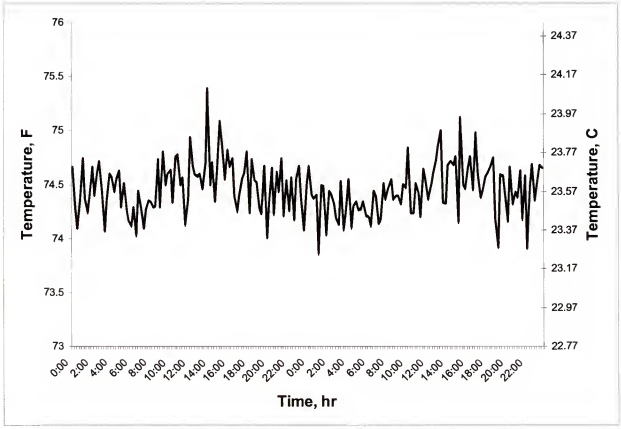

Figure 23. Bay 2 winter period temperature control history (48 hrs).

The Test Facility does not have access to the local water service. Therefore, a reservoir and pump system was installed outside the western equipment bay. Water pipe was installed from the pump/reservoir to each test bay. A fogger/mister designed for orchid watering was installed in each bay, downstream from a 24VAC water service solenoid valve. The nozzle was placed approximately 6.0 feet (1.8 m) in front of the air conditioner and between 6.5 ft (2.0 m) and 7.0 ft (2.1 m) from the floor, depending on the ceiling type. Bays 6 and 8 were configured in a slightly different manner.

Different levels of relative humidity were obtained by adding moisture in a controlled manner through this system. The three distinct control levels, already described, were investigated from July 15, 2001 through September, 2002. Additional equipment details are included in Appendix D.

Procedure

The test facility and its related equipment were used to obtain over 400 individual streams of data from July 15, 2001 to the present. Raw data were scaled and converted to engineering units and incorporated into an interactive computer control system and database. These tools were used to perform preliminary analysis and troubleshooting of the facility's day-to-day operation. With over 400 individual sensors taking data every 15 minutes, many different conditions and physical behaviors can be studied. Placement of a particular suite of sensors across the environment/roof interface has allowed for an investigation of solar-induced moisture transport through a shingle roof.

Data streams from Bays 2, 3 and 4 were used throughout this study, each bay for different reasons.

- Bay 2 has a cathedral ceiling equipped with a temperature/relative humidity sensor that characterizes the environmental conditions in the vented roof space of this style of construction. The moisture transport conditions that are observable

during the sunrise period are particularly evident in the cathedral-type ceilings. It should be noted that this phenomenon was observable in all types of attic spaces in this facility.

- Bay 3 was constructed with a typical flat ceiling attic space and was a close match to Bay 4. This match allowed a comparison to be made between a vented attic (Bay 3) and an un-vented attic (Bay 4).

A variety of data streams was used to illustrate the physical behavior of each type of construction. Some of the data streams were long-term (1+ years) and some were just a few hours long. Most data streams used in this study were 1–5 days in length. These were meant to illustrate and characterize typical physical events that occur in building spaces located in hot-humid climates.

CHAPTER 4
RESULTS AND ANALYSIS OF DATA

Modes of Moisture Transport

A review of the literature has shown that little work has been done investigating solar-induced moisture transport across roof structures. What little that has been done, was accomplished in more temperate climates, not hot-humid locations. With the advent of new building techniques and materials, this lack of knowledge becomes more critical. While not specifically designed to do so, the test facility previously described has become instrumental in providing insight into this phenomenon. To begin the analysis of this topic, a short evaluation of the moisture transport boundary envelope of a typical attic space is presented.

Figure 24 illustrates the three primary modes that moisture can be transported across the attic (or cathedral ceiling) boundary. One method not illustrated concerns the possibility of moisture transport across the exterior wall header. As new building techniques become more popular and fire codes are more stringently enforced, this mode will likely become even less important. Fire codes require that any penetrations through this header be sealed with an approved material. As shown, the three primary methods of transport are:

1. Transport across the ceiling plane
2. Attic ventilation (ridge and soffit)
3. Transport across the roof line

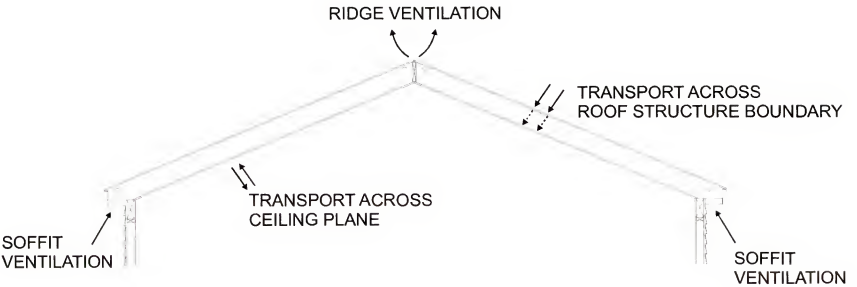

Figure 24. Cathedral/attic space moisture transport modes.

The most prominent transport mechanism of the three modes is driven by attic ventilation. Natural convection and pressure driven flows transport relatively large amounts of air and moisture into the attic space. Large amounts of air and moisture are also exhausted from the attic space via ridge vents in this particular case. The other transport mechanism is moisture which passes directly through specific building materials through a process of permeation. Moisture is also stored in building materials through a sorption process. Transport across the ceiling plane will be investigated first.

Ceiling Plane Transport

This transport mechanism is common to a large percentage of existing and new structures. In the absence of bulk water in the attic space, a simplified version of the conservation of mass equation (Equation 1) can be used to calculate water vapor transport across the ceiling plane. The driving force is quantified by the vapor pressure gradient between the attic and the conditioned spaces. The magnitude of the water vapor permeation is controlled by the permeability coefficient, M, described by Equation 2. This can be calculated by knowing the permeability property data for drywall and fiberglass insulation. A detailed look at this calculation procedure is presented in a later section.

The vapor pressure gradient can be calculated directly from known data. The 1997 *ASHRAE Handbook Fundamentals* (ASHRAE, 1997) illustrates a procedure whereby remaining thermodynamic properties can be calculated by knowing the dry bulb temperature, relative humidity and the barometric pressure. A brief discussion of this methodology follows:

1. The saturation pressure over liquid water can be calculated for each time increment from the following equation:

$$\ln(P_{ws}) = \frac{C_8}{T} + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}\ln T$$

where P_{ws} represents the saturation pressure, psia, and T is equal to the absolute temperature in Rankine. The values for the coefficients are found in the reference (ASHRAE, 1997).

2. The vapor pressure, P_w, is found simply from the relationship:

$$\phi = \frac{P_w}{P_{ws}}$$

where ϕ is the relative humidity

These equations can be incorporated into a spreadsheet where values for the attic vapor pressure and conditioned space vapor pressure can be calculated for each time step.

A temporal graph of the ceiling plane moisture transport of Bay 3 is shown in Figure 25. For the sake of example, this represents the half of the ceiling that is insulated with fiberglass insulation. The other half of the ceiling is insulated with blown in cellulose. Of particular interest is the extreme positive gradient that occurs each morning around sunrise. It should be noted that even though the numbers are small, the total mass transfer of water vapor from the attic to conditioned space for the five-day period is approximately 3.75 pounds of water (1.7 kg). Another important relationship present in these data is the fact that for this time period moisture is always being removed from the attic to conditioned space. The relationship between relative humidity and moisture content for gypsum board is shown in Figure 26. The equilibrium moisture content (EMC) of gypsum board at 50% relative humidity is approximately 0.3%. Mold can start to grow on surfaces once the relative humidity exceeds values of approximately 80%. l

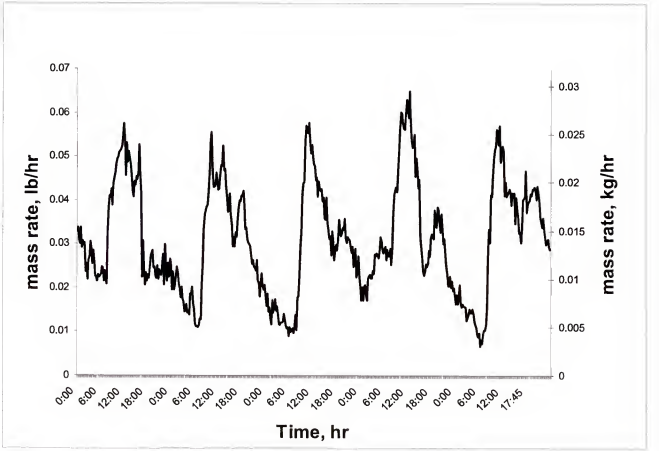

Figure 25. Moisture transport rates across ceiling plane boundary into Bay 3 conditioned space (August 1-5, 2002).

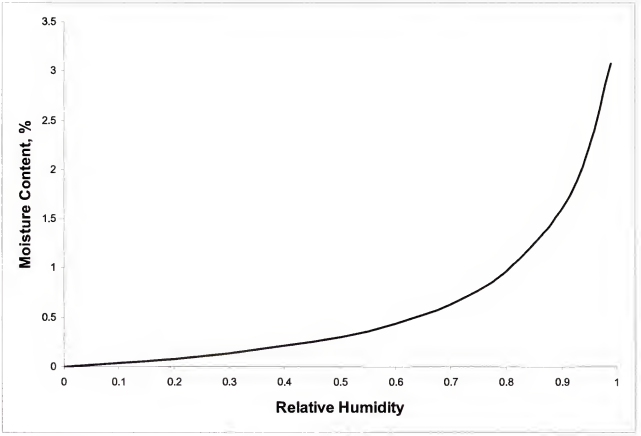

Figure 26. Equilibrium moisture content for gypsum board.

The EMC for gypsum board at this value is approximately 1.0%. For one half of the gypsum board in the ceiling of each bay (attic space), this represents an increase in total amount of water of just over 1.0 pound (1.08 lbs or about 0.5 kg). That amount of moisture is transported across the attic space boundary in less than two days. This example shows that even though the mass flow rates are small, construction techniques that tend to trap water vapor can create problems within days rather than months or years.

Attic Ventilation

Attic ventilation provides the most significant mechanism for the movement of moisture both into and out of attic and cathedral spaces. Figure 27 shows the amount of airflow out of the attic space for Bay 3 during the period from August 1 through August 5, 2002. By correlating these data with ambient conditions the influx of water vapor can also be calculated. These data are shown in Figure 28. Much has been made of this mechanism for driving moisture-laden air into attic spaces. As introduced earlier, very little research has been done on the complete behavior of attic ventilation. However, with the large amount of data collected by the Building Products Test Facility, some governing questions can be proposed and validated. Among them are:

- Correlations exist that relate relative humidity to moisture content in a variety of materials. Can the long-term (seasonal) validity of this relationship be confirmed? If so, what are the long-term moisture content values of the roof sheathing for both vented and non-vented attics?
- The relative humidity can be used to track moisture content, in the manner described above. Absolute humidity, or humidity ratio (kg of water per kg of dry air) can be used to account for moisture movement. What can the comparison of data concerning absolute humidity for vented and non-vented attics illustrate; especially when compared to the coincident ambient values?
- Finally, does a phenomenon exist that drives moisture into the attic from the roof line, and, if so, how is this excess moisture removed?

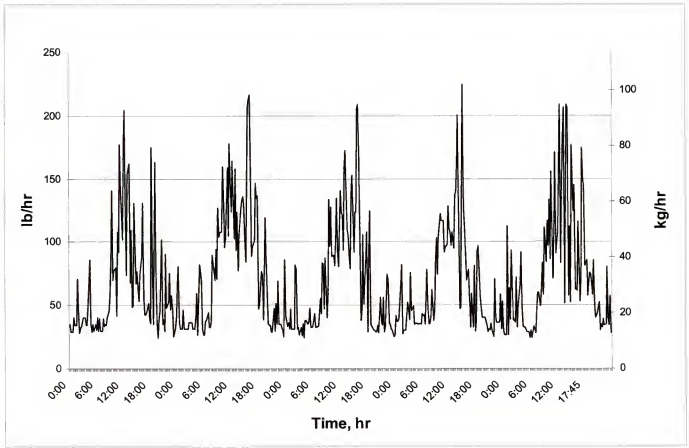

Figure 27. Attic ventilation rates from ridge vents, Bay 3 August 1-5, 2002.

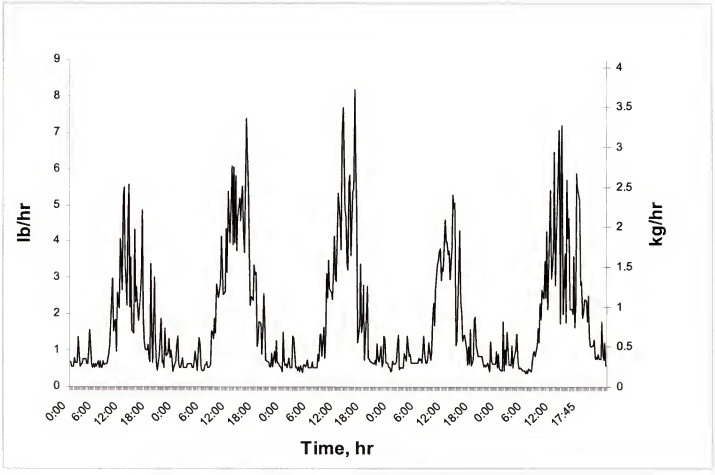

Figure 28. Attic water vapor rates entering Bay 3 soffits, August 1-5, 2002.

Moisture content correlation

It has been shown that correlations exist that relate the surrounding relative humidity to the equilibrium moisture content. Equation 5, presented in the Literature Review, shows the general form of this relationship. The relationship correlates the storage of moisture in the roof deck OSB with the relative humidity of the surrounding air in the attic space. Since the relative humidity was known for both Bay 3 and Bay 4 attic spaces, the moisture content of the OSB could be predicted from this relationship for every time increment. Figures 29 and 30 illustrate the data collected for September 15 and 16 for Bays 3 and 4. The entire data set of over 30,000 data points runs from September 15, 2001 through September 15, 2002. From this year long set of data and Equation 5, the average moisture content can be calculated for both vented and un-vented attic spaces located in a hot-humid climate. A predicted moisture content can be obtained from the calculated averages, based on empirical material properties and known boundary conditions:

- South facing roof sheathing, vented attic: Predicted moisture content = 8.7%
- South facing roof sheathing, un-vented attic: Predicted moisture content = 5.9%

Field measurements were also obtained to provide a comparison to predicted data. A portable moisture content meter provided by the Delmhorst Corporation was used. Meter reading corrections are provided for both temperature and species of wood. The correction for basswood is used for readings obtained from oriented strand board. At the time of measurement, temperatures were within the range that required no correction. The corrected average measured moisture content for these two attics is:

- South facing roof sheathing, vented attic: Measured moisture content = 8.1%
- South facing roof sheathing, un-vented attic: Measured moisture content = 6.6%

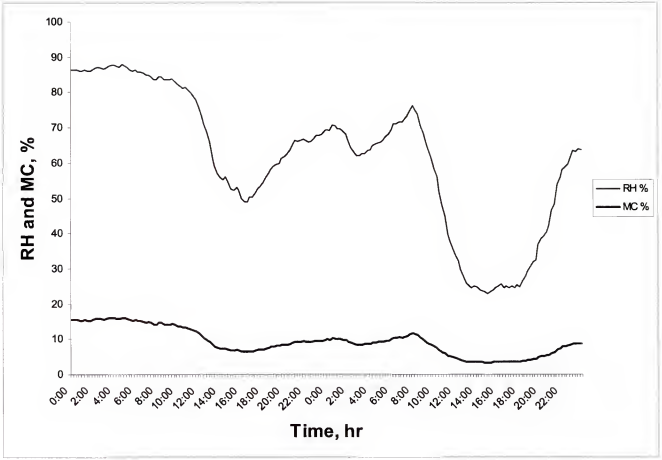

Figure 29. Vented attic (Bay 3) predicted moisture content values from known relative humidity conditions, September 15-16, 2002.

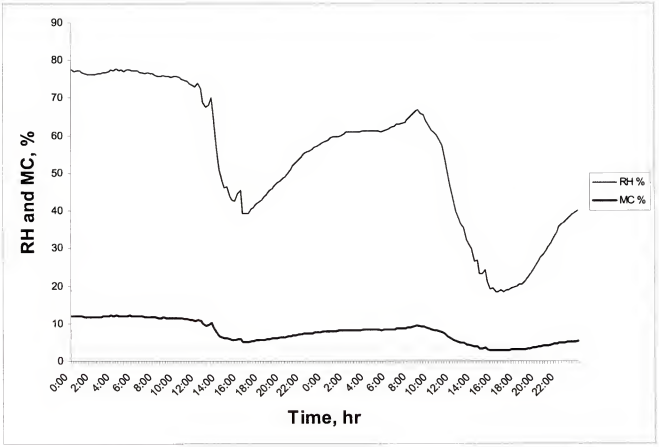

Figure 30. Unvented attic (Bay 4) predicted moisture content values from known relative humidity conditions, September 15-16, 2002

These values are in fair agreement with the predicted values of 8.7% and 5.9%, respectively. The measured value for the vented attic is 7% below the predicted value and the measured value for the unvented attic is 11% higher than the predicted value. Two other important conclusions can be drawn from this analysis:

1. Both averages are dryer than the guidelines for exposed wood in the southeastern United States (9 – 11%), and

2. The un-vented attic does have lower average moisture content. However, this lower average cannot be immediately attributed to the lack of ventilating to the hot-humid environment. It should be remembered that the moisture content is related to the relative humidity. The sealed attic of Bay 4 is insulated at the ceiling plane and not the roof plane. This results in a higher attic temperature profile in the absence of ventilation. This has a tendency to drive the relative humidity values lower.

Humidity ratio

While the relative humidity helps to describe the moisture content in adjacent porous building products, a brief look at the diurnal humidity ratio values (lbm/lbda, kgm/kgda) associated with vented and un-vented attics can also be of interest. Figure 31 provides information for humidity ratio values in vented and un-vented attic spaces. These data were taken from September 16 through September 20, 2001 and are typical of summertime behavior. There are several important issues found within these data that are described below:

- The vented attic is Bay 3. It is vented with continuous ridge and soffit vents. The humidity ratio within the attic space of Bay 3 stays below that of the ambient environment during this entire time period.

- The continuous ridge and soffit vents of Bay 4 were blocked to aid in the investigation of sealed attic behavior. The sealed attic exhibits the lowest humidity ratio in comparison with both ambient conditions and the vented attic during evening and early morning hours. However, at sunrise the sealed attic space undergoes a rapid increase in humidity ratio until the values are nearly double those of the external environment. This occurs during the afternoon hours. For this behavior to occur at all, moisture must be coming from somewhere that is at a higher level than the general external conditions would indicate.

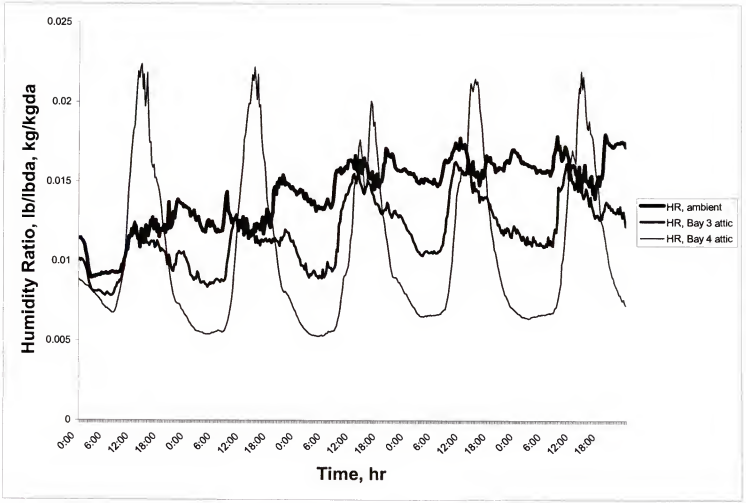

Figure 31. Humidity ratios for ambient, Bay 3 and Bay 4 conditions, September 16-20, 2002.

This short analysis shows that there is communication between the attic spaces and outside ambient conditions. Analysis of the phenomenon of solar-induced moisture transport provides answers to the remaining questions postulated in the Literature Review.

Solar Induced Moisture Transport

Frequency of occurrence

Personal observation of the roof structure of the test facility shows that condensation, or dew, collects on the roof during many nights. During early morning hours nighttime temperatures typically drop and the relative humidity rises. High humidity is a frequent occurrence in the early morning hours. At the same time, any surface that faces the night sky can lose heat to the mean radiant temperature of the dark sky. In this manner, a roof surface can, and often does, cool to temperatures below the ambient environment. When this happens at the same time that the humidity is approaching one hundred percent, condensation forms on the cooled surface.

Data collected from the test facility were surveyed from mid July 2001 through the beginning of February 2003. Investigating the behavior of the following specific data points helped evaluate whether condensation formed on the roof shingles:

- Ambient relative humidity: Nighttime radiant cooling of roof shingles of a very small amount can produce condensation when the ambient relative humidity approaches 100%. The database stores this value under the label of VRH27.
- Ambient temperature: This sensor was picked to provide a comparative baseline. The database stores this temperature under the label of Vtemp27.
- Roof temperature: Thermocouples are located in various places throughout the structure. Of particular interest are the ones located just under the roof shingles. Thermocouple TC29 is located on the lower part of the south facing section of the roof of Bay 2.

A database file was created for these sensors, on a month-by-month basis for the previously described time period. This file was then converted to an Excel spreadsheet format. A double conditional IF statement was performed on the resulting data file to flag the time intervals in which both of the following conditions were true:

- The ambient relative humidity was greater than 95%, and
- The underside of the shingles were more than two degrees Fahrenheit cooler than the coincident ambient temperature.

This time period included 573 days in which data were collected. Of these days, 43 had incomplete data during the early morning hours and were therefore not included in the analysis. Data were collected for over 50,000 time intervals. The dual-conditional IF statement was applied to each time period. It can be concluded from this information that condensation formed on the roof shingles more than 67% of the mornings. On a month-by-month basis, condensation formed the greatest number of mornings, 87% of the time, during April 2002. Condensation formed the least number of mornings, 55% of the time, during January 2002. An example of the spreadsheet format and the IF statement are included in Appendix E. Table 4 includes a month-by-month summary of these data. As these data show, condensation formed on the shingle roof of the test facility more than two-thirds of the days of the year for 2002.

Model development

The roof of the test facility is a typical shingle roof constructed with the following materials and boundary conditions (in order from outside in):

- Ambient environment
- Asphalt shingles and roofing nails
- Asphalt building paper and plastic-headed fasteners

Table 4. Month by month summary of roof surface condensation events (2002).

Month (2002)	% of Days That Condensation Occurred
January	55
February	57
March	66
April	87
May	71
June	65
July	81
August	70
September	69
October	67
November	62
December	61

- Oriented strand board
- Attic or cathedral space

A one-dimensional water vapor permeability equation was presented and defined as Equation 3. To calculate total rates of moisture transport for the Test Facility roof structure, this equation must be multiplied by the total cross-sectional area, A_T (ft^2, m^2). This form would be:

$$W_T = M_T A_T (P_{v1} - P_{v2})$$

where W_T represents the total moisture transport rate (lb/hr, kg/hr), the vapor permeability, M_T (lb/hr ft^2 psia, kg/hr m^2 Pa), is based on constant properties, and the vapor pressures, P_v (psia, Pa), are based on ambient conditions in the outdoors and attic spaces.

However, these initial rates are based on certain assumptions such as the materials being homogeneous and continuous, and the vapor permeability being a constant. If the concept of "as-built" conditions is introduced, the above equation must be modified to represent two parallel pathways and variable properties. Figure 32 represents an "as-built" configuration of the previously described roof structure. These two pathways can be represented by:

$$W_g = M_g A_g (P_{v1} - P_{v2})$$

where Wg is the vapor transport rate through the OSB and shingle gap area. The other path can be calculated from:

$$W_t = M_t A_t (P_{v1} - P_{v2})$$

where t represents the water vapor permeability through the original roof structure modified to reflect a reduced cross-sectional area coupled with a water vapor

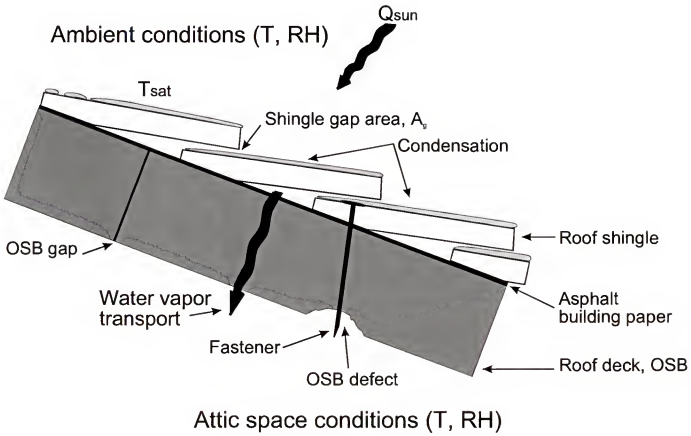

Figure 32 Solar-induced moisture transport across an "as-built" shingle roof boundary.

permeability coefficient modified to reflect a reduced thickness related to the OSB "defects" described in the subsequent moisture pathways section.

The total water vapor permeability for this case is simply calculated by addition:

$$W_T = W_g + W_t$$

This rate was further modified by recognizing that the water vapor permeability for OSB varies as a function of relative humidity, ϕ. The total water vapor permeability for this case was described as:

$$W_T = W_g + W_t(\phi)$$

where

$$W_t(\phi) = M_t(\phi) A_t (P_{v1} - P_{v2})$$

To complete the analysis, the vapor pressure differential was modified to reflect saturated vapor conditions on the surface of the shingles. Instead of P_{v1} representing the ambient conditions, $P_{sat.\ vap.}$ was used to represent actual conditions through the roof structure. The final water vapor permeation rate was then calculated from:

$$W_T = W_g (P_{sat.vap.}) + W_t (\phi, P_{sat.vap})$$

A brief description of the Test Facility "as-built" conditions follows:

- Shingle Gap: Inspection of the asphalt roofing shingles shows that a gap exits between each shingle layer. A "feeler" gauge was used to obtain a rough estimate of 0.020 in. (0.50 mm) for this gap. The south facing roof portion of each test bay (except Bays 5, 6, 7 and 8) has approximately 27 rows of shingles. These data were used to calculate a total gap area.

- OSB Gap: The 4 × 8 sheets of oriented strand board are held in place with each adjacent sheet by what are known as "hurricane clips". These clips create a gap between each sheet of OSB of approximately 0.0625 in. (1.6 mm). The linear dimension of theses gaps can be totaled for each test bay to yield a cross-sectional gap area.

- Attachment Penetrations: Plastic-headed nails were used to attach the roofing felt to the OSB. Roofing nails were used to attach the shingles to the roof structure. The south facing roof section of these test bays has approximately 900 total penetrations relating to these attachment details. A parametric analysis of

different possible gap diameters around each penetration shows this total penetration area to be much less (more than an order of magnitude) than the ones already calculated. This area was therefore ignored.

- OSB Defects: Nearly every penetration of the OSB creates a small area of defect on the side facing the attic space. The typical defect results in a chip separating from the surface of the OSB. The removal of the chip causes a depression with dimensions approximately $0.125 \times 0.50 \times 1.0$ in. ($3 \times 12 \times 25$ mm). Since water vapor permeability is a function of depth, this depression results in an increase in permeability around each penetration.

Analysis cases

Analysis of environmental conditions and the physical structure of the shingle roof shows both a source of moisture and multiple pathways between the ambient environment and the attic space. Rates of permeation can be calculated using the water vapor permeability equations presented in the Literature Review. A total of six separate cases will be analyzed:

- Case IA: The permeability of the roof structure will be analyzed as if all materials are homogeneous, with no defects introduced by manufacture or installation. The driving force will be calculated by the water vapor pressure differential across the attic space to the ambient environment.
- Case IB: This case is the same as Case IA except that the vapor pressure differential will include effects introduced by the condensation on the shingle surface.
- Case IIA: The permeability of the roof structure will include modifications that take into account previously discussed details such as shingle gap, OSB seams and OSB chips.
- Case IIB: This case is the same as Case IIA except that the vapor pressure differential will include effects introduced by the condensation on the shingle surface.
- Case IIIA: This case is the same as Case IIA except that the permeability of the OSB will be calculated with a relative humidity of 100%.
- Case IIIB: This case is the same as Case IIIA except that the vapor pressure differential will include effects introduced by the condensation on the shingle surface.

The total moisture flow rate through the roof structure can be calculated from Equation 3 modified to reflect total moisture flow rate through the cross-sectional roof area , where:

$$W_T = M_T A_T (P_{v1} - P_{v2})$$

With known vapor pressure data, this equation was solved for each time increment. The first case was calculated as follows:

$$M = \frac{1}{\frac{1}{perm_1} + \frac{1}{perm_2} + \frac{1}{perm_3}}$$

where $perm_1$ = permeability of the roof shingle
$perm_2$ = permeability of the asphalt roof paper
$perm_3$ = permeability of the oriented strand board (OSB)

$$perm_1 = \frac{0.0375 \text{ perm-inches}}{0.090 \text{ inches of shingle}}$$

where perm has units of grains/hr-ft^2-in Hg

$perm_1$ = 0.4167 grains/hr-ft^2-in Hg

In a similar manner,

$perm_2$ = 14.0 grains/hr-ft^2-in Hg
$perm_3$ = 1.55 grains/hr-ft^2-in Hg

$$M = \frac{1}{\frac{1}{0.4167} + \frac{1}{14.0} + \frac{1}{1.55}}$$

M = 0.321 grains/hr-ft^2-in Hg

Convert this to more familiar units

M = 0.321 grains/hr-ft^2-in Hg * 1 lb/ 7000 grains * in Hg/ 0.491 psia

$$M = \left(0.321 \frac{grains}{hr \cdot ft^2 \cdot inHg}\right)\left(\frac{1.0 \cdot lb}{7000 \cdot grains}\right)\left(\frac{1.0 \cdot inHg}{0.491 \cdot psia}\right)$$

$M = 9.34 \times 10^{-5}$ lb/hr-ft^2-psia

The values for all three primary cases in both sets of units are included in Table 5. The secondary cases (Ib, IIb, IIIb) use the same permeation coefficient with the vapor pressure gradient driven by condensation on the roof instead of the global ambient conditions.

Table 5. Aggregate permeation coefficients.

Permeation Coefficient	Case Ia	Case IIa	Case IIIa
M, lb/hr ft^2 psia	9.34×10^{-5}	11.7×10^{-5}	13.6×10^{-5}
M, kg/hr m^2 Pa	0.662×10^{-7}	0.829×10^{-7}	0.963×10^{-7}

With the roof area known and the vapor pressure gradient across the roof given by the sensor data, the water vapor transport, W (lb/hr) can be calculated for each time increment. The SI units corresponding to perm-inch are kg/s-m-Pa.

These data show that by including actual characteristics of installed building materials the permeation coefficient is increased by nearly 46%. An even larger effect is noticed when the vapor pressure differential is investigated. Moisture flow analyses are often performed by using the outdoor environment's ambient condition as a boundary condition. Knowledge of the roof shingle temperature and condensation state can allow a more accurate boundary condition to be used. A detailed look at two selected days can quantify the magnitude of water vapor, or moisture transport, that is produced by these physical conditions.

It has already been shown that the climate conditions at this site frequently produce condensation on the roof of the test facility. When the sun heats this water layer at dawn, the vapor pressure at the shingle surface increases significantly. Unfortunately, since the Building Products Test Facility was not designed to look at this exact physical

behavior, there are no sensors placed at the surface of the shingle. Therefore handheld measurements were obtained to check the validity of this assumption. A portable temperature, relative humidity meter was used to obtain data at the inlet of the soffit vents to Bay 2 and at the outlet of the ridge vents to the same test bay. Data were taken from 7:00 a.m. until 9:30 a.m. on December 23, 2002 and again from 7:00 a.m. until 10:00 a.m. on February 26, 2003. Analysis of these two days and in particular these two "sunrise" periods yields several conclusions:

- The ambient vapor pressure driving force is calculated from the differential between ambient conditions and attic conditions. All of the data, except one time interval, show a positive gradient into the attic. That one data point is essentially zero. The full data set with calculations for these two days is included in Appendix G for further examination.
- Water vapor permeation into the attic increases by factors between 1.4 and nearly 300 when taking into account actual construction techniques and the greater vapor pressure differential associated with roof surface condensation. These data are shown in the Total Rate Multiplier column included in the spreadsheet data in Appendix G.
- Humidity ratio calculations show that as the permeation rate peaks, the roof ventilation system exhausts more moisture than enters via the soffits. This supports the hypothesis that solar induced moisture transport occurrs across the roof boundary. See Figure 33 for details.

As was stated before, the original sensor set was not designed or placed to specifically investigate solar induced moisture transport. The most obvious problem relates to the lack of relative humidity data at the soffit inlet and ridge exhaust. This is why the handheld data set was required for verification. However, the signature or profile unique to this phenomenon is well illustrated by the temperature and relative humidity sensors placed in all but four of the attic spaces (sensors not placed in attic spaces of Bays 1, 5, 7 and 12). One of these sensors will be investigated in detail to provide further understanding.

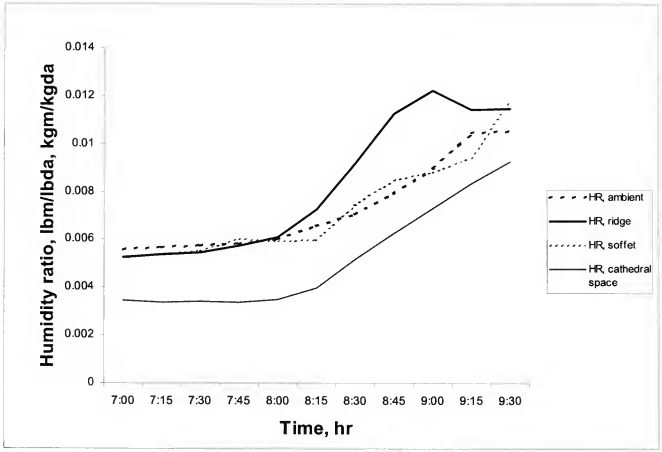

Figure 33. Solar induced moisture transport, humidity ratio behavior during sunrise conditions, December 23, 2002

Data collected from the sensor located in the cathedral ceiling space of Bay 2 were collected and averaged for the entire month of August 2002. Figure 34 illustrates the monthly averaged profile for the cathedral ceiling relative humidity. This monthly profile was divided into four distinct regions and they are explained below:

- Region 1: During this period (approximately midnight to 7:00 a.m.) the relative humidity stabilized as the ambient conditions also reached a temporary equilibrium. Typically the ambient temperature approached the dewpoint temperature which resulted in the relative humidity reaching 100%, or nearly so. This was a typical scenario during the nighttime hours. A slight upward trend of these data was often present. This started in the late evening hours of the previous day when the shingles reached the dewpoint condition.

- Region 2: This period (roughly 7:00 a.m. to 10:30 a.m.) showed a marked increase in the relative humidity just as the sun struck the roof. As the roof temperature increased at the same time, it is clear that the absolute humidity also increased.

- Region 3: As ambient conditions heated up during a typical summer day (10:30 a.m. to 4:30 p.m.), the relative humidity dropped inside the attic or cathedral ceiling space. So while the absolute amount of moisture in the air was high when conditions reached 120ºF (48.9ºC) and 30% RH, it should be remembered that the attic wood products were absorbing water in relation to the relative humidity.

- Region 4: This period (4:30 p.m. to midnight) represented a transition from daytime heating to nighttime stabilization.

The cathedral ceilings exhibited the most noticeable increase in Region 2. It should be noted that all of the test bay attic spaces, regardless of construction or operation, exhibited this behavior.

Knowing that this phenomenon occurs more than two out of every three nights during each year allows an estimation procedure to be performed. Previous data have shown that the average moisture content for the vented attic was found to be approximately 8%. It would require the addition of nearly 14 pounds (6.2 kg) of water to raise the moisture content level from 8% to 15% for the southern exposure of the roof of

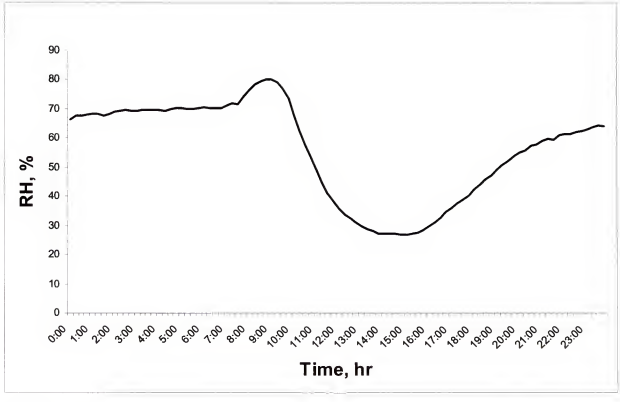

Figure 34. Cathedral space, hourly averaged relative humidity, Bay 2 August 2002.

an individual test bay. Summing all of the moisture transport through the southern exposure of the roof of Test Bay 2 during the 24-hour period of December 23, 2002, shows that a total of 0.117 pounds (0.053 kilograms) of water were transported through the structure and into the attic/cathedral space. If this water was trapped by the placement of a vapor barrier located on the attic side of the roof sheathing, the long-term moisture content of the OSB could increase. Such a vapor barrier could be a continuously applied metal foil radiant barrier or closed-cell (or semi-permeable) insulation.

Exposed wood products such as OSB can reach a moisture content level of 15% or more when located in a localized relative humidity environment of 80+%. A moisture content level of 15% can be reached after 120 days similar to December 23, 2002.

CHAPTER 5
CONCLUSION

The behavior of attic and cathedral spaces was investigated with the aid of a full-scale test facility constructed in Gainesville, Florida. A series of questions was posed, analyses conducted and the following conclusions can be made.

1. Data obtained from the Building Products Test Facility showed that nighttime conditions produced condensation on the roof shingle surface. A combination of frequent high levels of relative humidity and sub-cooling due to radiant cooling produced temperatures at the shingle surface that were below the dewpoint.

2. Over 600 days of data were analyzed with the aid of a simple algorithm. While all of the data supported the conclusion, only calendar year 2002 data were reported for completeness. Over 67% of the mornings in this time period exhibited conditions that produced condensation at the shingle surface. On a monthly basis, the maximum occurred in April at 87% and the minimum occurred in January at 55%.

3. Moisture transport through the roof structure was calculated for six different scenarios. The initial case was based on continuous isotropic material properties and ambient weather conditions. The case that resulted in maximum rates of moisture transport included the following effects:

    - Gaps between shingle layers
    - Gaps between adjacent sheets of OSB roof decking
    - Defects introduced by shingle and asphalt building paper fasteners
    - Increase in OSB water vapor permeability based on surrounding relative humidity conditions
    - Increased boundary condition vapor pressure differentials brought about by solar heating of the condensation layer on the shingle surface

    The maximum rates of moisture transport were nearly 300 times the rates found in the initial case.

4. Two adjacent test bays were investigated for differences in the long-term moisture content values for vented and un-vented attic spaces. Published correlations used

5. the known relative humidity data to calculate the moisture content values for the OSB roof sheathing. These predicted values compared well with direct measurement values. In both cases the OSB sheathing or decking moisture content values were well within limits prescribed by industry standards.

6. Handheld measurement data were used to show that a removal mechanism exists for the solar-induced moisture transported into the attic space. Typical continuous soffit and ridge vents showed higher water vapor content measurements exiting from the ridge than were entering at the soffits.

This study has shown that typical shingle roof construction in Florida's hot-humid climate produces a situation that frequently provides a moisture pathway into attic and cathedral spaces. Furthermore, a limited dataset also shows a removal mechanism using a combination of continuous soffit and ridge vents. Long-term data shows acceptable roof sheathing moisture content levels whether the attic is vented or not. However, some currently suggested construction techniques involving un-vented attic spaces and roof sheathings coated with semi-permeable insulation or other impermeable membranes would have to be analyzed carefully with regards to solar-induced moisture transport providing moisture that could be trapped within the wood roof sheathing. However small these rates are, the long-term effect would need to be quantified before these construction techniques could be accepted.

APPENDIX A
SENSOR INFORMATION

1. **Thermocouple assembly specifications**
Thermocouple assemblies were purchased in bulk from Omega Engineering, Inc. Their facilities are located at:

Omega Engineering, Inc.
One Omega Drive
Stamford, Connecticut 06907-0047
800-848-4286

The assembly part number is 5TC-GG-T-24_36-SMP-M, where:

TC: Thermocouple
GG: Glass braid insulation
T: Type T thermocouple
24: 24 AWG
36: 36-inch lead length
SMP: Subminiature connector
M: Male connector

The lead lengths are made with special limits of error thermocouple wire, details of which are found with the thermocouple extension wire details.

2. **Temperature/Relative Humidity Sensor Specifications:**
A combination temperature and relative humidity (T/RH) sensor was chosen from products made by the Vaisala Group of Helsinki, Finland. The sensors for this test facility were purchased from the United States office of this company, located at:

Vaisala, Inc.
100 Commerce Way
Woburn, MA 01801-1068 1-781-933-4500

The –60 series was chosen to provide a 4-20 mA output signal. The combined T/RH sensor has a part number of HMD60Y. The supply voltage chosen was 18VDC, therefore the load resistor (Rl) is equal to 0.0 ohms. The error for the typical environmental range of these sensors is:

RH: +/- 2.0%
T: +/- 0.5°C

3. **Airflow velocity sensor**
Natural convective and pressure driven airflows in cathedral and attic spaces were measured by airflow sensors based on the hot-wire anemometer technique. The sensors used for this facility were modified Eliminator 3000 models manufactured by Ebtron, Inc (1-800-232-8766). These sensors measured both air velocity and temperature of the flow field. The accuracy of the velocity sensor is 10 feet per minute for the modified range of 0-100 feet per minute. The accuracy of the temperature sensor is 0.18°F with a maximum of 0.36°F.

Velocity output: 4-20 mA = 0-100 feet per minute
Temperature Output: 0-5VDC = 0-200 F

4. **Veris Industries kW/kWh Meter**
Each test bay is equipped with a kW meter to measure energy consumption. These meters are manufactured by:
Veris Industries
10831 SW Cascade Blvd
Portland, Oregon 97223
800-354-8556
These meters can output data in either pulse format or a 4-20mA signal. The pulse otput was not compatible with the NI equipment so the 4-20 mA format was used. The system accuracy of the meter is +/- 1% from 10% to 100% of the maximum rated current of the current transducers.

5. **LI200X Pyranometer**
This pyranometer is calibrated to the daylight spectrum between 400 and 100 nm. The output of the LI200X is in current form. An included resistor converts the current into voltage form for datalogging. The maximum error of this sensor in natural daylight is +/- 5% with +/-3% being typical. The sensitivity of this sensor is 0.2kW m^{-2} mV^{-1}. This sensor was purchased through:
Campbell Scientific, Inc.
815 West 1800 North
Logan, Utah 84321-1784

6. **Wind Monitor**
The wind monitor chosen for this facility is manufactured by the R. M. Young company and sold through Campbell Scientific, Inc. of Logan, Utah. Model number 05103 was chosen for cost purposes. The wind speed is proportional to output pulses that use the following expression:
U = MX + B, where:
M = multiplier
X = pulses per second
B = offset
The wind direction sensor uses an excitation voltage of 5VDC to produce an output of 0. 071 degrees per millivolt. There is a deadband between 355 and 360 degrees.

7. **Barometric Pressure Sensor**
A PTB 100 Analog Barometer was purchased from The Vaisala Group. The accuracy of this sensor is +/- 30 Pascals at room temperature. The output voltage signal is 0-5VDC. This sensor was purchased from the U.S. office of the Vaisala Group at:
Vaisala, Inc.
100 Commerce Way
Woburn, MA 01801-1068
1-781-933-4500

8. **Thermocouple Accessories**
A variety of thermocouple accessories were used on this project. All were obtained from Omega Engineering located at:

Omega Engineering, Inc.
One Omega Drive
Stamford, Connecticut 06907-0047
800-848-4286

Thermocouple extension wire was purchased in 1000' rolls with the specification part number of EXPP-T-20-UL, where:

EXPP = extension wire with polyvinyl jacket and insulation
T= Type T thermocouple
20 = 20 AWG
UL = the wire is UL rated

Multi-pair extension wire was also purchased in 1000' rolls of 12 and 16 channels. The part number for these items are 12TX20PP and 16TX20PP, respectively. Special limits of error wire was specified for the single channel extension wire and the multi-pair extension cable. The error for this wire is published at +/- 0.5ºC or 0.4%.

9. Thermocouple and Other Terminal Blocks

The TC-2095 terminal block is equipped with 32 type T thermocouple channels. Col-junction compensation is accomplished through the use of a factory-installed thermistor. Accuracy is 0.5C for SCXI-1102 modules and repeatability is 0.35ºC. Other analog input modules, chassis and terminal blocks used in this facility, include:

- SCXI 1100 Analog Input Modules
- SCXI 1000 and 1001 Chassis
- SCXI 1300 and 1303 Modules
- SCXI 1326 High Voltage Modules

These modules and terminal blocks can be obtained from the National Instruments company, located at:

National Instruments Corporation
11500 N Mopac Expressway
Austin, TX 78759-3504
Tel: 512-683-0100
Fax: 512-683-8411

10. Thermocouple and Other Terminal Blocks

The TC-2095 terminal block is equipped with 32 type T thermocouple channels. Col-junction compensation is accomplished through the use of a factory-installed thermistor. Accuracy is 0.5ºC for SCXI-1102 modules and repeatability is 0.35ºC. Other analog input modules, chassis and terminal blocks used in this facility, include:

- SCXI 1100 Analog Input Modules
- SCXI 1000 and 1001 Chassis
- SCXI 1300, 1303 and 1326 Modules

These modules and terminal blocks can be obtained from the National Instruments company, located at:

National Instruments Corporation
11500 N Mopac Expressway
Austin, TX 78759-3504
Tel: 512-683-0100
Fax: 512-683-8411

APPENDIX B
DATA ACQUISITION SOFTWARE

```
ClsTCReader.das
Dim calGndOffset As Variant
Dim lerr As Long
Dim cjcTemp As Double
Dim readSpec As New CWAIReadSpec
Public Function getTCData() As Variant
'scans all 9 TC modules and returns array of scaled values
    Dim index As Integer
    Dim chanNo As Integer
    Dim tempArray(287) As Double
    Dim ModuleData As Variant
    For index = 1 To 9
        ModuleData = scanModule(index)
        For chanNo = 0 To 31
            tempArray(chanNo + (index - 1) * 32) = ModuleData(chanNo)
        Next
    Next
getTCData = tempArray
End Function
Private Function scanModule(modNumber As Integer) As Variant
'gets raw binary thermocouple data as *** rawBinaryData *** variant
    Dim chanVolts() As Variant
    Dim binaryMultiplier As Variant
    Dim rawBinaryData As Variant
    Dim binaryOffset As Variant
    Dim index As Integer
    Dim numberChan As Integer
    Dim scaledTemps As Variant
    getCalGnd (modNumber)
    getCJCTemp (modNumber)
    With frmMainForm
        .AI.Reset
        readSpec.ReturnDataType = cwaiBinaryCodes
        .AI.AcquiredDataEnabled = False
        .AI.Channels.RemoveAll
        .AI.Channels.Add "ob0! sc1!" & modNumber & "! 0:31", 0.01, -0.01
        .AI.ScanClock.Frequency = 320
        .AI.Configure
```

```
        binaryMultiplier = .AI.Channels.Item(1).ScaleMultiplier
        binaryOffset = .AI.Channels.Item(1).ScaleOffset
        .AI.Start
        lerr = .AI.Read(100, rawBinaryData, readSpec)
        .AI.Stop
        If lerr <> 0 Then MsgBox "DAQ Read: " + CStr(lerr)
        numberChan = .AI.Channels.NChannels
        ReDim chanVolts(numberChan)
        For index = 0 To numberChan - 1
            avgBinaryData =
            .CWStat1.Mean(.CWArray1.IndexArray(rawBinaryData, Array(index,
            Null)))
            chanVolts(index) = (avgBinaryData - calGndOffset) * binaryMultiplier +
            binaryOffset
        Next
        lerr = .dqTools.ConvertTC(cwT, cjcTemp, cwFahrenheit, chanVolts,
        scaledTemps)
        .AI.Reset
    End With
    scanModule = scaledTemps
End Function
Private Sub getCalGnd(modNumber As Integer)
Dim calgndtemp As Variant
'gets raw binary CALGND data returned as *** calGndOffset *** variant
    With frmMainForm
        .AI.Reset
        .AI.AcquiredDataEnabled = False
        readSpec.ReturnDataType = cwaiBinaryCodes
        .AI.Channels.RemoveAll
        .AI.Channels.Add "ob0! sc1!" & modNumber & "! calgnd", 0.01, -0.01
        .AI.Configure
        .AI.Start
            lerr = .AI.Read(100, calgndtemp, readSpec)
        .AI.Stop
        .AI.Reset
        calGndOffset = .CWStat1.Mean(calgndtemp)
    End With
End Sub
Private Sub getCJCTemp(modNumber As Integer)
' gets cold junction value and passes data as *** CJCTemp *** variant
    Dim volts As Variant
    Dim TempCJC As Variant
    With frmMainForm
        .AI.Reset
        readSpec.ReturnDataType = cwaiScaledData
        .AI.AcquiredDataEnabled = False
```

```
        .AI.Channels.RemoveAll
        .AI.Channels.Add "ob0!sc1!md" & modNumber & "!MTEMP", 2, 0
        .AI.ScanClock.Frequency = 100
        .AI.Configure
        .AI.Start
        lerr = .AI.Read(1, volts, readSpec)
        .AI.Stop
        If Err <> 0 Then
            MsgBox "CJC Acquire: " + CStr(Err)
            Else:
                lerr = .dqTools.ConvertThermistor(cwVoltRef, 2.5, 5000, cwCelsius,
                volts(0), TempCJC)
                cjcTemp = TempCJC
        End If
        .AI.Reset
    End With
End Sub
```

Clsvoltreader.das

```
Public Function getVoltageData() As Variant
    Dim chanVolts As Variant
    Dim avgChanVolts As Variant
    Dim index As Integer
    Dim numberChan As Integer
    Dim readSpec As New CWAIReadSpec
With frmMainForm
    .AI.Reset
    readSpec.ReturnDataType = cwaiScaledData
    .AI.AcquiredDataEnabled = False
    .AI.Channels.RemoveAll
    .AI.Channels.Add "ob1! sc2!md1! 0:31", 5, 0
    .AI.Channels.Add "ob1! sc2!md2! 0:31", 5, 0
    .AI.Channels.Add "ob1! sc2!md3! 0:31", 5, 0
    .AI.Channels.Add "ob1! sc2!md4! 0:31", 5, 0
    .AI.Channels.Add "ob1! sc2!md5! 0:31", 5, 0
    .AI.Channels.Add "ob1! sc2!md6! 0:31", 5, 0
    .AI.ScanClock.Frequency = 97
    .AI.Configure
    .AI.Start
    lerr = .AI.Read(97, chanVolts, readSpec)
    .AI.Stop
    If lerr <> 0 Then MsgBox "DAQ Read: " + CStr(lerr)
    numberChan = .AI.Channels.NChannels
    ReDim avgChanVolts(numberChan)
    For index = 0 To numberChan - 1
        avgChanVolts(index) = .CWStat1.Mean(.CWArray1.IndexArray(chanVolts,
        Array(index, Null)))
```

```
    Next
    .AI.Reset
End With
    getVoltageData = avgChanVolts
End Function
```

Clsweather.das

```
Public Function getWeatherData() As Variant
    Dim scaledData(5) As Double '5 channels of weather data
    'temperature
    scaledData(0) = scanChannel(0, 5, 0)
    'humidity
    scaledData(1) = scanChannel(1, 5, 0)
    'barometric pressure
     scaledData(2) = scanChannel(2, 5, 0
    'pyronometer
     scaledData(3) = scanChannel(6, 1, 0)
    'wind direction
     scaledData(4) = scanChannel(4, 5, 0)
    scaledData(5) = getWindSpeed     'wind speed
    getWeatherData = scaledData
End Function
Private Function getWindSpeed() As Double
    Dim chanVolts As Variant
    Dim readSpec As New CWAIReadSpec
    Dim df As Variant
    Dim autoSpec As Variant
    Dim freqOutput As Variant
    Dim powerPeak As Variant
    With frmMainForm
    .aiWeather.Reset
    readSpec.ReturnDataType = cwaiScaledData
    .aiWeather.AcquiredDataEnabled = False
    .aiWeather.Channels.RemoveAll
    .aiWeather.Channels.Add "ob1!sc2!md7!5", 10, -10
    .aiWeather.ScanClock.Frequency = 4096
    .aiWeather.Configure
    .aiWeather.Start
    lerr = .aiWeather.Read(2048, chanVolts, readSpec)
    .aiWeather.Stop
    If lerr <> 0 Then MsgBox "DAQ Read: " + CStr(lerr)
    .dsp1.AutoPowerSpectrum chanVolts, 1 / 2048, autoSpec, df
    .dsp1.PowerFrequencyEstimate autoSpec, -1, 0, 0, df, 2048, freqOutput,
    powerPeak
    getWindSpeed = freqOutput
    .aiWeather.Reset
    End With
```

```
End Function
Private Function scanChannel(chanNumber As Integer, upper As Integer, lower
As Integer) As Double
Dim chanVolts As Variant
Dim readSpec As New CWAIReadSpec
With frmMainForm
.aiWeather.Reset
readSpec.ReturnDataType = cwaiScaledData
.aiWeather.AcquiredDataEnabled = False
.aiWeather.Channels.RemoveAll
.aiWeather.Channels.Add "ob1!sc2!md7!" & chanNumber, upper, lower
.aiWeather.ScanClock.Frequency = 97
.aiWeather.Configure
.aiWeather.Start
lerr = .aiWeather.Read(97, chanVolts, readSpec)
.aiWeather.Stop
If lerr <> 0 Then MsgBox "DAQ Read: " + CStr(lerr)
scanChannel = frmMainForm.CWStat1.Mean(chanVolts)
.aiWeather.Reset
End With
    End Function
```

APPENDIX C
CONTROL SYSTEM SOFTWARE

Mainform Controls

```
Option Explicit
Dim secsUntilNextDatalog As Integer
Public WithEvents dbConn As ADODB.Connection
Public Sub writeToDigitalPort()
    Dim output1 As Double
    Dim output2 As Double
    Dim I As Integer
    Dim lErr As Long
    output1 = 2 ^ 24
    output2 = 2 ^ 24
    For I = 0 To 11
        If isCool(i) Then output1 = output1 – 2 ^ I
        If isHeat(i) Then output1 = output1 – (2 ^ (I + 12))
        If isHumidify(i) Then output2 = output2 – 2 ^ I
    Next
    lErr = outputControls.SingleWrite(output1 – 1)
    If lErr <> 0 Then
        MsgBox CStr(lErr)
    End If
    lErr = outputControls2.SingleWrite(output2 – 1)
    If lErr <> 0 Then
        MsgBox CStr(lErr)
    End If
End Sub
Private Sub AI_AcquiredData(Voltages As Variant, BinaryCodes As Variant)
    numLoops = numLoops + 1
    scaleData (Voltages)
    doControls
    getRunTime
    displayData
    If Day(Now) <> dayOfMonth Then resetControls
    If numLoops = secsUntilNextDatalog Then
        numLoops = 0
        AI.Stop
        dateTimeStamp = Now
        'attempt to make database connection
        Set dbConn = New ADODB.Connection
```

```
        mainForm.dbConn.Provider = "sqloledb"
        mainForm.dbConn.Open
        "server=10.5.33.200;uid=sa;pwd=datamonger;database=certainteed", , ,
        adAsyncConnect
        secsUntilNextDatalog = secsToNext
        AI.Start
    End If
    Text1.Text = secsUntilNextDatalog – numLoops
End Sub
Private Sub dbConn_ConnectComplete(ByVal pError As ADODB.Error, adStatus As
ADODB.EventStatusEnum, ByVal pConnection As ADODB.Connection)
    If adStatus = adStatusErrorsOccurred Then GoTo bail
        txtStatus.Text = "Succesfull Datalog at: " & Now
        dataLog
        dbConn.Close
        Exit Sub
bail:
    Set dbConn = Nothing
    txtStatus.Text = "Datalog error: " & pError
    Err.Clear
End Sub
Private Sub Form_Load()
    Set dbConn = New ADODB.Connection
    resetForm
    resetHardware
    resetControls
    displayData
End Sub
Private Sub resetHardware()
    Dim lErr As Long
    AI.Device = 1
    AI.Channels.RemoveAll
    AI.Channels.Add "ob0! Sc1! Md1! 0:23", 5, 0
    AI.Channels.Add "ob0! Sc1! Md2! 0:11", 5, 0
    AI.Nscans = 100
    AI.ScanClock.Frequency = 100
    lErr = AI.Configure
    If lErr <> 0 Then MsgBox "DAQ Configure: " + CStr(lErr)
    lErr = AI.Start
    If lErr <> 0 Then MsgBox "DAQ Start: " + CStr(lErr)
    outputControls.Reset
    outputControls2.Reset
    outputControls.Ports(0).Assignment = cwdioOutput
    outputControls2.Ports(0).Assignment = cwdioOutput
    writeToDigitalPort
End Sub
```

```
Private Sub resetForm()
    Dim I As Integer
    secsUntilNextDatalog = secsToNext
    For I = 0 To 11
        Temp(i) = 75
        RH(i) = 60
        tempControl(i).Value = 75
        humidityControl(i).Value = rhMinimum
        humidityControl(i).Axis.Minimum = rhMinimum
        txtTempControl(i).Text = tempControl(i).Value
        txtHumidControl(i).Text = humidityControl(i).Value
        tempSetPoints(i) = txtTempControl(i).Text
        humiditySetPoints(i) = txtHumidControl(i).Text
    Next
End Sub
Private Sub resetControls()
        Dim I As Integer
        For I = 0 To 11
            isCool(i) = False
            isHeat(i) = False
            isHumidify(i) = False
        Next
        rightNow = Timer
        dayOfMonth = Day(Now)
        resetControlTimer
End Sub
Public Sub resetControlTimer()
    Dim I As Integer
    For I = 0 To 11
        holdTimer(i).aircoState = acOffMode
        holdTimer(i).aircoTimer = rightNow
        holdTimer(i).humidState = False
        holdTimer(i).humidTimer = rightNow
    Next
End Sub
Private Sub displayData()
    Dim I As Integer
    For I = 0 To 11
        txtTemp(i).Text = Temp(i)
        txtRH(i).Text = RH(i)
        txtKW(i).Text = dailyKWh(i)
        heatLED(i).Value = isHeat(i)
        □ilowa(i).Value = isCool(i)
        humidifyLED(i).Value = isHumidify(i)
        txtHeatRun(i).Text = dailyHeatTime(i)
        txtCoolRun(i).Text = dailyCoolTime(i)
```

```
        txtRHRun(i).Text = dailyRhTime(i)
    Next
End Sub
Private Sub Form_Unload(Cancel As Integer)
    Dim I As Integer
    Dim lErr As Long
    lErr = outputControls.SingleWrite(2 ^ 24 – 1)
    If lErr <> 0 Then
        MsgBox CStr(lErr)
    End If
    lErr = outputControls2.SingleWrite(2 ^ 24 – 1)
    If lErr <> 0 Then
        MsgBox CStr(lErr)
    End If
End Sub
Private Sub tempControl_PointerValueChanged(index As Integer, ByVal Pointer As
Long, Value As Variant)
        Dim newSetPoint As Double
        newSetPoint = tempControl(index).Value
        txtTempControl(index).Text = newSetPoint
        tempSetPoints(index) = newSetPoint
End Sub
Private Sub humidityControl_PointerValueChanged(index As Integer, ByVal Pointer
As Long, Value As Variant)
    Dim newSetPoint As Double
    newSetPoint = humidityControl(index).Value
    txtHumidControl(index).Text = humidityControl(index).Value
    humiditySetPoints(index) = newSetPoint
End Sub
Private Function secsToNext() As Integer
    Dim mins As Integer
    Dim secs As Integer
    Dim theTime As Date
    theTime = Now
    mins = Minute(theTime)
    secs = Second(theTime)
    secsToNext = ((15 – (mins Mod 15) – 1) * 60) + (60 – secs)
End Function
```

Modcontrols

```
Option Explicit
Public holdTimer(11) As holdTimerPrototype
Private lErr As Long
Public rightNow As Double
Public Sub doControls()
    Dim index As Integer
    rightNow = Timer 'rightNow = time since midnight in seconds
```

```
    For index = 0 To 11
        checkTemps (index)
        checkRH (index)
    Next
    mainForm.writeToDigitalPort
End Sub
Private Sub checkTemps(channelNumber As Integer)
    If Temp(channelNumber) > tempSetPoints(channelNumber) + 1 Then   'cooling
    required
        enableCooling (channelNumber)
        Else
            If Temp(channelNumber) < tempSetPoints(channelNumber) – 1 Then
            'heating required
                enableHeating (channelNumber)
                Else
                'temperature is within 2 degree deadband attempt to shut unit down
                    shutDownAirCO (channelNumber)
            End If
    End If
End Sub
Private Sub checkRH(channelNumber As Integer)
    If RH(channelNumber) < humiditySetPoints(channelNumber) Then   ' too dry,
    spray water
        enableHumidification (channelNumber)
        Else: 'has met humidity □ilowatt□nts.
        ShutDownHumidifier (channelNumber)
    End If
End Sub
Private Sub enableCooling(channelNumber As Integer)
    Select Case holdTimer(channelNumber).aircoState
        Case acOffMode 'airco off
        'Attempt to go into cooling mode. Check 240 sec delay timer
            If ((rightNow – holdTimer(channelNumber).aircoTimer) > acOffTime)
            Then
            'delay exceeded, turn ON channel I, reset timer
                isCool(channelNumber) = True
                isHeat(channelNumber) = False
                holdTimer(channelNumber).aircoTimer = rightNow
                holdTimer(channelNumber).aircoState = coolMode 'switch to cooling
                mode
            End If
        Case heatMode 'heating state
        'do not allow transistion from heat directly to cool
        'reset timer and turn unit off
            shutDownAirCO (channelNumber)
    End Select
```

```
End Sub
Private Sub enableHeating(channelNumber As Integer)
    Select Case holdTimer(channelNumber).aircoState
        Case coolMode 'was in cooling state
        'do not allow transistion from cool directly to heat
        'reset timer and turn off channel I
            shutDownAirCO (channelNumber)
        Case acOffMode 'airco was off
        'Attempt to go into heat mode. Check 240 sec delay timer
            If ((rightNow – holdTimer(channelNumber).aircoTimer) > acOffTime)
            Then
            'delay exceeded, turn ON channel I, reset timer
                isCool(channelNumber) = False
                isHeat(channelNumber) = True
                holdTimer(channelNumber).aircoTimer = rightNow
                holdTimer(channelNumber).aircoState = heatMode 'switch to heat
                mode
            End If
    End Select
End Sub
Private Sub enableHumidification(channelNumber As Integer)
    If holdTimer(channelNumber).humidState Then 'Already running.
        'Limit runtime
        If (rightNow – holdTimer(channelNumber).humidTimer) > rhOnTime Then
            'time expired turn off humidity
            shutDownHumidifier (channelNumber)
        End If
        Else: 'was off. Attempt to turn on and reset timer.
            If (rightNow – holdTimer(channelNumber).humidTimer) > rhOffTime
            Then
                isHumidify(channelNumber) = True    'off timer expired
                holdTimer(channelNumber).humidState = True
                holdTimer(channelNumber).humidTimer = rightNow
            End If
    End If
End Sub
Private Sub shutDownHumidifier(channelNumber As Integer)
    isHumidify(channelNumber) = False
    holdTimer(channelNumber).humidState = False        'not on
    holdTimer(channelNumber).humidTimer = rightNow     'reset timer
End Sub
Private Sub shutDownAirCO(channelNumber As Integer)
    If Not (holdTimer(channelNumber).aircoState = acOffMode) Then
    'airco was in state other than OFF. Check runtime.
        If ((rightNow – holdTimer(channelNumber).aircoTimer) > acOnTime) Then
        'one minute run time □ilowatt. OK to shut down
```

```
            isCool(channelNumber) = False
            isHeat(channelNumber) = False
            holdTimer(channelNumber).aircoState = acOffMode 'switch to OFF mode
            holdTimer(channelNumber).aircoTimer = rightNow     'reset OFF timer
        End If
    End If
End Sub
```

Moddatalogger

```
Option Explicit
Public Sub dataLog()
    insertKW
    insertRunTime
    resetValues
End Sub
Private Sub resetValues()
    Dim I As Integer
    For I = 0 To 11
        rhRunTime(i) = 0
        heatRunTime(i) = 0
        totalKWSeconds(i) = 0
        coolRunTime(i) = 0
    Next I
End Sub
Private Function insertKW() As String
    Dim sql As String
    Dim I As Integer
    Dim sensorID As String
    Dim data As Double
    With mainForm
    .dbConn.BeginTrans
    For I = 1 To 12
        sensorID = "Kw" & I
        data = totalKWSeconds(I – 1)  'datalog kwseconds
        sql = "stp_Ins_data '" & sensorID & "','" & dateTimeStamp & "'," & data
        .dbConn.Execute sql
    Next
    .dbConn.CommitTrans
    End With
End Function
Private Function insertRunTime()
    Dim sql As String
    Dim I As Integer
    Dim sensorID As String
    Dim data As Double
    With mainForm
    .dbConn.BeginTrans
```

```
        For I = 1 To 12
            sensorID = "acRun" & I
            data = coolRunTime(I – 1)
            sql = "stp_Ins_data '" & sensorID & "','" & dateTimeStamp & "',"  &
            data
            .dbConn.Execute sql
            sensorID = "heatRun" & I
            data = heatRunTime(I – 1)
            sql = "stp_Ins_data '" & sensorID & "','" & dateTimeStamp & "',"  &
            data
            .dbConn.Execute sql
            sensorID = "rhRun" & I
            data = rhRunTime(I – 1)
            sql = "stp_Ins_data '" & sensorID & "','" & dateTimeStamp & "',"  &
            data
            .dbConn.Execute sql
        Next
        .dbConn.CommitTrans
    End With
End Function
```

Modglobal

```
Option Explicit
'****************** status indicators  *****************
Public isHeat(11) As Boolean
Public isCool(11) As Boolean
Public isHumidify(11) As Boolean
'****************** setpoint controls  *****************
Public humiditySetPoints(11) As Double
Public tempSetPoints(11) As Double
'****************** input data channels  ******************
Public Temp(11) As Double
Public RH(11) As Double
Public KW(11) As Double
'******************  calculated fields  ******************
Public totalKWSeconds(11) As Double
Public dailyKWh(11) As Double
Public coolRunTime(11) As Long
Public dailyCoolTime(11) As Long
Public heatRunTime(11) As Long
Public dailyHeatTime(11) As Long
Public rhRunTime(11) As Long
Public dailyRhTime(11) As Long
'****************** control status structure  ************
Type holdTimerPrototype
    aircoState As Tristate
    'aircoState = -2 >>> both off   <mixed>
```

```
    'aircoState = -1 >>> heat mode  <true>
    'aircoState =  0 >>> cool mode  <false>
    humidState As Boolean
    'humidState false = humidifier not on
    'humidstate true = humidification on
    aircoTimer As Double 'time since midnight
    humidTimer As Double 'time since midnight
End Type
'******************  delay timer constants ********************
Public Const acOnTime = 60     'must run for at least one minute
Public Const acOffTime = 240   'must stay off for 4 minutes
Public Const rhOnTime = 30     'continue humidification for 30 seconds
Public Const rhOffTime = 120   'do not re humidify for 4 minutes
Public Const datalogInterval = 60 * 15 '15 minute datalog cycle
Public Const coolMode = TristateFalse
Public Const heatMode = TristateTrue
Public Const acOffMode = TristateMixed
Public Const rhMinimum = 30
'****************** misc time variables ************************
Public dayOfMonth As Integer    'the day of the month storage
Public numLoops As Long         'counter for datalog interval
Public dateTimeStamp As String
Modscale
Option Explicit
Public Sub scaleData(Voltages As Variant)
    Dim I As Integer
'*********************************************************************
    For I = 0 To 11                 'scale temperatures (channels 0-11)
        If Voltages(I, 0) > 0.9 Then
            Temp(i) = roundNumber(11.25 * ((Voltages(I, 0) / 0.249) – 4) – 4)
            Else:
            Temp(i) = 0
        End If
    Next
        '*************************************************************

******

    For I = 0 To 11                 'scale humidity (channels 12-24)
        If Voltages(I + 12, 0) > 0.9 Then
            RH(i) = roundNumber((25 * (Voltages(I + 12, 0)) – 25))
            Else:
            RH(i) = 0
        End If
     Next
'*********************************************************************
```

```
    For I = 0 To 11                'scale kwSeconds (channels 24-36)
        If Voltages(I + 24, 0) > 1 Then
            KW(i) = Format(Voltages(I + 24, 0), "###.###")
            Else:
            KW(i) = 0
        End If
        totalKWSeconds(i) = totalKWSeconds(i) + KW(i) 'totalize □ilowatt data
        dailyKWh(i) = dailyKWh(i) + KW(i) / 3600
        Next
End Sub
Private Function roundNumber(dblInput As Double) As Integer
    Dim intTemp As Integer
    intTemp = Int(dblInput)
    If Int((dblInput – intTemp) * 10) > 4 Then intTemp = intTemp + 1
    roundNumber = intTemp
End Function
Public Sub getRunTime()
    Dim I As Integer
    For I = 0 To 11
        If dayOfMonth < Day(Now) Then
            ' past midight. Reset counter stacks
            dailyHeatTime(i) = 0
            dailyCoolTime(i) = 0
            dailyRhTime(i) = 0
            dailyKWh(i) = 0
        End If
        If isHeat(i) Then
            heatRunTime(i) = heatRunTime(i) + 1
            dailyHeatTime(i) = dailyHeatTime(i) + 1
        End If
        If isCool(i) Then
            coolRunTime(i) = coolRunTime(i) + 1
            dailyCoolTime(i) = dailyCoolTime(i) + 1
        End If
        If isHumidify(i) Then
            rhRunTime(i) = rhRunTime(i) + 1
            dailyRhTime(i) = dailyRhTime(i) + 1
        End If
    Next
End Sub
```

APPENDIX D
MISCELLANEOUS HARDWARE INFORMATION

1. **Test Bay Air Conditioners**
   Individual air conditioners with heat strips were installed in each test bay. The model specified for this facility is:
   General Electric Wall-mount Air Conditioner, Model # AJJ09DF
   Wall Case Model # RAB48, with stamped aluminum grille
   These units were manufactured by the General Electric Company of Louisville, Kentucky and GE Appliances can be contacted at 800.626.2000

2. **Pump/Reservoir Equipment**
   Most of the water delivery system for the humidity control equipment was purchased from:
   Myers Septic and Well Drilling
   224 N.E. 16th Avenue
   Gainesville, FL
   The reservoir was purchased from a local farm supply business and the solenoid valves were purchased from:
   Flow-Technology, Inc.
   49 Century Street (32211)
   PO Box 8889
   Jacksonville, FL 32239
   904.721.0822
   The solenoid valves are manufactured by the Skinner Division of Parker and were purchased in particular because of the low power draw of the coil.

APPENDIX E
DUAL CONDITIONAL IF EXAMPLE

Date	Time	VRH27	VTemp27	TC29	VRH3	VTemp3	DelT	DewCond
08/01/2001	0:00	100.030	74.0255	72.69	71.50	74.24	1.34	0
08/01/2001	0:15	100.030	73.6430	72.68	73.83	74.24	0.96	0
08/01/2001	0:30	100.030	73.6565	72.80	76.74	74.21	0.86	0
08/01/2001	0:45	100.030	73.7150	72.63	74.65	74.04	1.08	0
08/01/2001	1:00	100.030	73.6205	72.36	73.42	73.74	1.26	0
08/01/2001	1:15	100.030	73.6385	72.34	73.36	73.58	1.30	0
08/01/2001	1:30	100.030	73.3640	72.48	75.21	73.68	0.88	0
08/01/2001	1:45	100.030	73.3505	72.00	74.08	73.54	1.35	0
08/01/2001	2:00	100.030	73.1705	71.65	74.18	73.56	1.52	0
08/01/2001	2:15	100.030	72.8375	71.29	74.26	73.33	1.55	0
08/01/2001	2:30	100.030	72.6665	71.46	77.29	73.59	1.21	0
08/01/2001	2:45	100.030	72.6125	71.42	75.79	73.43	1.19	0
08/01/2001	3:00	100.030	72.7475	71.54	75.56	73.13	1.21	0
08/01/2001	3:15	98.370	72.5855	71.54	75.73	72.96	1.05	0
08/01/2001	3:30	97.673	72.2885	71.18	75.55	72.91	1.10	0
08/01/2001	3:45	98.543	71.9330	70.41	73.73	72.62	1.52	0
08/01/2001	4:00	98.873	72.1535	70.02	72.97	72.36	2.14	1
08/01/2001	4:15	99.703	71.6045	69.74	72.88	72.00	1.87	0
08/01/2001	4:30	100.030	71.4695	69.41	72.67	71.93	2.06	1
08/01/2001	4:45	100.030	71.2355	69.10	72.99	71.66	2.13	1
08/01/2001	5:00	100.030	71.1770	68.67	74.12	71.67	2.51	1
08/01/2001	5:15	100.030	72.1895	68.50	74.17	71.57	3.69	1
08/01/2001	5:30	98.268	72.2570	68.74	74.32	71.51	3.52	1
08/01/2001	5:45	99.063	71.8835	69.23	75.91	71.62	2.65	1
08/01/2001	6:00	100.030	71.6315	69.51	75.80	71.83	2.12	1
08/01/2001	6:15	99.270	71.8430	69.40	74.97	71.60	2.45	1
08/01/2001	6:30	99.820	71.2355	69.24	74.63	71.42	1.99	0

If the roof sheathing temperature, TC 29 is more than 2F (1.11C) less than the ambient temperature, VTemp27 AND the relative humidity is greater than 95%, then condensation will form on the roof shingle surface.

The dual conditional IF statement is represented by: =IF(AND(H2>2,C2>95),1,) where H2 represents the temperature depression between ambient and the roof sheathing and C2 is the ambient relative humidity.

The integer 1 in the Dew Cond. column represents a flag that shows condensation has formed.

APPENDIX F
ADDITIONAL EARLY MORNING DATA

Date	Time	Baro1	Vtemp 27	VRH27	EB Temp7	EB Temp8	Vel7	Vel8	TC29	TC30	VRH3
12/23/02	0:00	1020.81	46.84	100.03	53.32	46.86	11.86	6.72	42.65	42.70	34.58
12/23/02	0:15	1020.69	46.53	100.03	51.76	47.62	8.27	9.17	42.58	42.52	34.74
12/23/02	0:30	1020.53	46.02	100.03	51.76	46.83	12.43	9.10	42.25	42.10	34.37
12/23/02	0:45	1020.32	45.78	100.03	52.52	46.06	12.25	7.50	41.82	41.73	35.53
12/23/02	1:00	1020.30	45.43	100.03	52.54	46.07	10.29	7.57	41.47	41.53	36.14
12/23/02	1:15	1020.34	45.32	100.03	52.52	45.26	10.22	9.11	41.22	41.19	35.75
12/23/02	1:30	1020.31	44.86	100.03	52.52	45.29	11.02	7.27	40.95	40.84	35.88
12/23/02	1:45	1020.34	44.24	100.03	51.73	45.27	12.28	12.68	40.83	40.68	35.75
12/23/02	2:00	1020.26	44.62	100.03	51.77	44.50	9.51	4.75	40.44	40.55	36.25
12/23/02	2:15	1020.27	44.38	100.03	51.76	44.50	10.82	5.44	40.27	40.24	36.42
12/23/02	2:30	1020.15	44.81	100.03	50.98	43.69	18.52	8.33	40.15	40.13	35.42
12/23/02	2:45	1020.12	44.52	100.03	50.99	44.47	11.83	4.73	40.02	40.14	36.41
12/23/02	3:00	1020.31	44.99	100.03	50.98	43.70	11.83	5.27	40.05	40.12	37.51
12/23/02	3:15	1020.45	44.08	100.03	50.97	43.71	16.16	12.70	39.78	39.94	37.52
12/23/02	3:30	1020.36	44.10	100.03	50.99	42.93	11.19	9.94	39.58	39.90	37.70
12/23/02	3:45	1020.20	44.34	100.03	50.97	42.92	16.14	12.29	39.51	39.84	37.99
12/23/02	4:00	1020.24	44.23	100.03	49.42	43.69	23.26	11.91	39.43	39.41	36.50
12/23/02	4:15	1020.21	44.14	100.03	47.89	45.28	25.27	9.09	39.74	39.45	37.31
12/23/02	4:30	1020.07	43.81	100.03	47.87	44.50	16.08	8.27	39.63	39.25	36.66
12/23/02	4:45	1020.27	43.26	100.03	49.43	43.71	9.30	6.75	39.29	38.91	36.18
12/23/02	5:00	1020.36	43.08	100.03	49.42	43.33	11.30	10.65	39.05	38.81	36.28
12/23/02	5:15	1020.42	43.08	100.03	47.08	43.73	18.08	8.33	38.78	38.54	36.16
12/23/02	5:30	1020.57	42.84	100.03	47.10	43.73	9.91	8.30	38.65	38.42	36.27
12/23/02	5:45	1020.62	42.45	100.03	48.66	42.93	9.10	9.53	38.52	38.32	36.26
12/23/02	6:00	1020.71	43.05	100.03	49.44	42.16	8.29	8.34	38.32	38.13	36.26
12/23/02	6:15	1020.79	42.64	100.03	49.46	42.18	8.66	7.17	38.17	38.03	37.53
12/23/02	6:30	1020.89	42.58	100.03	49.43	42.15	11.48	5.85	38.15	38.21	37.93
12/23/02	6:45	1021.14	42.57	100.03	49.44	41.39	7.87	6.73	37.88	38.17	38.89
12/23/02	7:00	1021.39	42.00	100.03	48.63	41.35	9.85	7.26	37.82	38.02	38.54
12/23/02	7:15	1021.56	42.46	100.03	48.64	41.33	15.78	8.68	37.83	38.04	37.47
12/23/02	7:30	1021.84	42.72	100.03	48.68	42.16	11.88	9.07	38.32	38.58	37.85
12/23/02	7:45	1022.09	43.05	100.03	47.11	43.72	16.17	9.05	39.46	39.82	37.62
12/23/02	8:00	1022.15	43.95	100.03	48.65	43.70	19.35	8.69	41.43	42.10	38.38
12/23/02	8:15	1022.12	46.34	100.03	47.89	47.64	15.36	9.65	46.66	48.17	42.50
12/23/02	8:30	1022.12	48.18	100.03	50.20	53.09	31.48	18.56	53.95	55.48	51.66
12/23/02	8:45	1022.21	51.36	100.03	54.84	57.76	31.33	19.38	60.96	63.15	57.21
12/23/02	9:00	1022.33	54.64	100.03	59.51	63.26	31.56	14.98	68.21	70.76	60.38
12/23/02	9:15	1022.39	58.81	100.03	64.98	67.96	38.28	18.59	75.61	77.49	61.90
12/23/02	9:30	1022.39	61.25	91.76	70.37	71.04	43.68	32.29	85.58	88.70	60.93
12/23/02	9:45	1022.45	62.81	85.35	76.54	72.54	40.87	53.09	94.02	98.74	56.12
12/23/02	10:00	1022.45	63.15	82.50	81.86	73.98	41.62	64.11	100.79	107.01	49.80
12/23/02	10:15	1022.31	65.46	79.09	86.66	76.41	53.67	40.37	107.22	114.51	43.78
12/23/02	10:30	1022.40	66.08	73.94	91.18	77.05	65.68	94.33	111.65	119.01	38.01
12/23/02	10:45	1022.03	67.09	72.73	96.76	78.75	62.85	68.76	116.43	124.58	34.24
12/23/02	11:00	1021.87	68.36	66.06	100.55	80.18	64.06	51.81	120.65	129.11	30.46
12/23/02	11:15	1021.52	70.07	57.37	104.44	81.41	68.89	44.56	124.36	133.88	27.38
12/23/02	11:30	1021.20	69.67	56.04	108.41	81.05	66.74	34.41	126.06	135.38	23.73
12/23/02	11:45	1021.06	70.22	53.35	109.96	81.81	69.42	59.71	127.69	136.98	21.44
12/23/02	12:00	1020.63	70.08	54.54	111.47	81.76	78.60	55.11	128.71	137.89	19.71
12/23/02	12:15	1020.27	70.88	54.90	111.32	81.62	89.27	75.71	129.59	139.20	18.90
12/23/02	12:30	1019.85	70.61	55.69	112.28	81.77	62.46	29.93	129.72	140.45	18.70
12/23/02	12:45	1019.59	71.05	55.01	112.97	82.48	70.65	71.30	131.19	142.34	18.14
12/23/02	13:00	1019.35	70.75	52.91	113.80	81.79	60.12	47.38	130.28	141.02	16.74
12/23/02	13:15	1018.89	71.37	54.25	115.24	83.22	68.22	65.39	131.15	141.67	16.61
12/23/02	13:30	1018.35	71.45	52.03	114.57	81.74	74.97	44.12	129.35	140.28	16.22
12/23/02	13:45	1017.95	72.21	50.42	112.95	82.45	66.99	43.32	128.02	138.71	16.31
12/23/02	14:00	1017.66	72.11	48.57	115.40	83.34	58.23	34.05	128.38	137.87	15.70
12/23/02	14:15	1017.67	72.21	48.45	115.28	82.47	75.03	41.55	126.95	136.02	15.54
12/23/02	14:30	1017.59	73.32	47.95	111.38	80.88	59.73	34.63	123.31	131.97	15.53
12/23/02	14:45	1017.33	72.19	48.03	110.62	81.69	64.54	51.28	122.37	130.71	15.61
12/23/02	15:00	1017.11	71.69	48.61	109.81	80.95	57.64	50.71	118.59	125.64	15.87
12/23/02	15:15	1017.09	71.81	49.62	108.33	80.23	59.47	47.83	115.45	123.02	16.50
12/23/02	15:30	1017.00	71.70	48.99	105.93	80.11	83.56	81.60	114.55	121.45	17.09
12/23/02	15:45	1017.00	71.23	50.18	104.47	78.68	63.09	41.41	110.02	115.98	17.95

Date	Time	VTemp3	Ridge T	Ridge RH	Soffit T	Soffit RH	amb psia	Pws amb	Pw amb	W amb	Pws ridge
12/23/02	0:00	57.26					14.81	1.58E-01	1.58E-01	6.72E-03	
12/23/02	0:15	57.20					14.80	1.56E-01	1.56E-01	6.64E-03	
12/23/02	0:30	57.03					14.80	1.53E-01	1.53E-01	6.52E-03	
12/23/02	0:45	56.80					14.80	1.52E-01	1.52E-01	6.46E-03	
12/23/02	1:00	56.89					14.80	1.50E-01	1.50E-01	6.37E-03	
12/23/02	1:15	56.72					14.80	1.49E-01	1.49E-01	6.34E-03	
12/23/02	1:30	56.52					14.80	1.47E-01	1.47E-01	6.23E-03	
12/23/02	1:45	56.40					14.80	1.43E-01	1.43E-01	6.09E-03	
12/23/02	2:00	56.18					14.80	1.45E-01	1.45E-01	6.18E-03	
12/23/02	2:15	56.01					14.80	1.44E-01	1.44E-01	6.12E-03	
12/23/02	2:30	55.98					14.80	1.46E-01	1.47E-01	6.22E-03	
12/23/02	2:45	55.81					14.80	1.45E-01	1.45E-01	6.15E-03	
12/23/02	3:00	56.06					14.80	1.48E-01	1.48E-01	6.26E-03	
12/23/02	3:15	55.91					14.80	1.42E-01	1.43E-01	6.05E-03	
12/23/02	3:30	55.85					14.80	1.43E-01	1.43E-01	6.05E-03	
12/23/02	3:45	55.82					14.80	1.44E-01	1.44E-01	6.11E-03	
12/23/02	4:00	55.61					14.80	1.43E-01	1.43E-01	6.08E-03	
12/23/02	4:15	55.50					14.80	1.43E-01	1.43E-01	6.06E-03	
12/23/02	4:30	55.48					14.79	1.41E-01	1.41E-01	5.99E-03	
12/23/02	4:45	55.23					14.80	1.38E-01	1.38E-01	5.86E-03	
12/23/02	5:00	55.36					14.80	1.37E-01	1.37E-01	5.82E-03	
12/23/02	5:15	55.11					14.80	1.37E-01	1.37E-01	5.82E-03	
12/23/02	5:30	55.12					14.80	1.36E-01	1.36E-01	5.76E-03	
12/23/02	5:45	55.02					14.80	1.34E-01	1.34E-01	5.68E-03	
12/23/02	6:00	54.94					14.80	1.37E-01	1.37E-01	5.81E-03	
12/23/02	6:15	55.02					14.80	1.35E-01	1.35E-01	5.72E-03	
12/23/02	6:30	54.85					14.81	1.35E-01	1.35E-01	5.70E-03	
12/23/02	6:45	54.94	Begin portable data measurements				14.81	1.34E-01	1.34E-01	5.70E-03	
12/23/02	7:00	54.83	43.80	88.00	44.50	85.50	14.81	1.32E-01	1.32E-01	5.57E-03	1.41E-01
12/23/02	7:15	54.88	43.15	92.00	43.90	89.75	14.82	1.34E-01	1.34E-01	5.67E-03	1.37E-01
12/23/02	7:30	54.77	42.50	96.10	43.40	94.00	14.82	1.35E-01	1.35E-01	5.73E-03	1.34E-01
12/23/02	7:45	54.86	44.60	93.30	46.00	92.50	14.82	1.37E-01	1.37E-01	5.80E-03	1.45E-01
12/23/02	8:00	55.09	46.70	91.30	46.80	88.50	14.82	1.42E-01	1.42E-01	6.01E-03	1.57E-01
12/23/02	8:15	55.82	55.00	80.00	54.90	66.00	14.82	1.55E-01	1.55E-01	6.59E-03	2.14E-01
12/23/02	8:30	57.76	61.10	80.80	58.80	71.50	14.82	1.66E-01	1.66E-01	7.06E-03	2.67E-01
12/23/02	8:45	60.18	72.80	66.00	66.30	62.50	14.83	1.87E-01	1.87E-01	7.96E-03	3.99E-01
12/23/02	9:00	62.91	79.10	58.00	71.00	55.20	14.83	2.11E-01	2.11E-01	8.99E-03	4.93E-01
12/23/02	9:15	66.00	86.30	43.00	72.00	57.00	14.83	2.46E-01	2.46E-01	1.05E-02	6.22E-01
12/23/02	9:30	69.47	93.00	35.00	78.60	57.00	14.83	2.68E-01	2.46E-01	1.05E-02	7.67E-01
12/23/02	9:45	73.08	103.74	End portable data			14.83	2.83E-01	2.42E-01	1.03E-02	
12/23/02	10:00	77.02	112.01	measurements.			14.83	2.87E-01	2.36E-01	1.01E-02	
12/23/02	10:15	80.69	119.51	Ridge T estimated			14.83	3.11E-01	2.46E-01	1.05E-02	
12/23/02	10:30	84.13	124.01	after 9:30 am.			14.83	3.17E-01	2.35E-01	1.00E-02	
12/23/02	10:45	86.95	129.58				14.82	3.29E-01	2.39E-01	1.02E-02	
12/23/02	11:00	89.69	134.11				14.82	3.43E-01	2.27E-01	9.67E-03	
12/23/02	11:15	92.26	138.88				14.82	3.64E-01	2.09E-01	8.90E-03	
12/23/02	11:30	94.44	140.38				14.81	3.59E-01	2.01E-01	8.57E-03	
12/23/02	11:45	96.31	141.98				14.81	3.66E-01	1.95E-01	8.31E-03	
12/23/02	12:00	97.65	142.89				14.80	3.64E-01	1.99E-01	8.46E-03	
12/23/02	12:15	98.63	144.20				14.80	3.74E-01	2.05E-01	8.76E-03	
12/23/02	12:30	99.15	145.45				14.79	3.71E-01	2.07E-01	8.81E-03	
12/23/02	12:45	100.09	147.34				14.79	3.76E-01	2.07E-01	8.83E-03	
12/23/02	13:00	100.62	146.02				14.78	3.73E-01	1.97E-01	8.41E-03	
12/23/02	13:15	101.14	146.67				14.78	3.81E-01	2.06E-01	8.81E-03	
12/23/02	13:30	101.17	145.28				14.77	3.82E-01	1.99E-01	8.48E-03	
12/23/02	13:45	101.03	143.71				14.76	3.92E-01	1.97E-01	8.43E-03	
12/23/02	14:00	101.22	142.87				14.76	3.90E-01	1.90E-01	8.09E-03	
12/23/02	14:15	101.21	141.02				14.76	3.92E-01	1.90E-01	8.10E-03	
12/23/02	14:30	100.51	136.97				14.76	4.07E-01	1.95E-01	8.33E-03	
12/23/02	14:45	99.73	135.71				14.75	3.91E-01	1.88E-01	8.02E-03	
12/23/02	15:00	99.17	130.64				14.75	3.85E-01	1.87E-01	7.99E-03	
12/23/02	15:15	97.98	128.02				14.75	3.86E-01	1.92E-01	8.19E-03	
12/23/02	15:30	96.88	126.45				14.75	3.85E-01	1.89E-01	8.05E-03	
12/23/02	15:45	95.52	120.98				14.75	3.79E-01	1.90E-01	8.12E-03	

Date	Time	Pw ridge	W ridge	Pws soffit	Pw soffit	W soffit	Pws VRH3	Pw VRH3	W VRH3	Pws shingle est
12/23/02	0:00						2.32E-01	8.04E-02	3.39E-03	
12/23/02	0:15						2.32E-01	8.05E-02	3.40E-03	
12/23/02	0:30						2.30E-01	7.92E-02	3.35E-03	
12/23/02	0:45						2.29E-01	8.12E-02	3.43E-03	
12/23/02	1:00						2.29E-01	8.29E-02	3.50E-03	
12/23/02	1:15						2.28E-01	8.15E-02	3.44E-03	
12/23/02	1:30						2.26E-01	8.12E-02	3.43E-03	
12/23/02	1:45						2.25E-01	8.05E-02	3.40E-03	
12/23/02	2:00						2.23E-01	8.10E-02	3.42E-03	
12/23/02	2:15						2.22E-01	8.09E-02	3.42E-03	
12/23/02	2:30						2.22E-01	7.86E-02	3.32E-03	
12/23/02	2:45						2.21E-01	8.03E-02	3.39E-03	
12/23/02	3:00						2.22E-01	8.34E-02	3.53E-03	
12/23/02	3:15						2.21E-01	8.30E-02	3.51E-03	
12/23/02	3:30						2.21E-01	8.32E-02	3.52E-03	
12/23/02	3:45						2.21E-01	8.38E-02	3.54E-03	
12/23/02	4:00						2.19E-01	7.99E-02	3.38E-03	
12/23/02	4:15						2.18E-01	8.13E-02	3.44E-03	
12/23/02	4:30						2.18E-01	7.99E-02	3.38E-03	
12/23/02	4:45						2.16E-01	7.81E-02	3.30E-03	
12/23/02	5:00						2.17E-01	7.87E-02	3.33E-03	
12/23/02	5:15						2.15E-01	7.77E-02	3.28E-03	
12/23/02	5:30						2.15E-01	7.80E-02	3.29E-03	
12/23/02	5:45						2.14E-01	7.77E-02	3.28E-03	
12/23/02	6:00						2.14E-01	7.74E-02	3.27E-03	
12/23/02	6:15						2.14E-01	8.04E-02	3.40E-03	
12/23/02	6:30						2.13E-01	8.08E-02	3.41E-03	
12/23/02	6:45	**Begin portable data measurements**					2.14E-01	8.31E-02	3.51E-03	
12/23/02	7:00	1.24E-01	5.25E-03	1.45E-01	1.24E-01	5.24E-03	2.13E-01	8.20E-02	3.46E-03	1.41E-01
12/23/02	7:15	1.26E-01	5.36E-03	1.41E-01	1.27E-01	5.38E-03	2.13E-01	7.99E-02	3.37E-03	1.37E-01
12/23/02	7:30	1.29E-01	5.46E-03	1.39E-01	1.30E-01	5.52E-03	2.12E-01	8.04E-02	3.39E-03	1.34E-01
12/23/02	7:45	1.36E-01	5.74E-03	1.53E-01	1.42E-01	6.01E-03	2.13E-01	8.01E-02	3.38E-03	1.45E-01
12/23/02	8:00	1.44E-01	6.09E-03	1.58E-01	1.40E-01	5.92E-03	2.15E-01	8.24E-02	3.48E-03	1.57E-01
12/23/02	8:15	1.71E-01	7.27E-03	2.13E-01	1.41E-01	5.96E-03	2.21E-01	9.38E-02	3.96E-03	2.14E-01
12/23/02	8:30	2.15E-01	9.17E-03	2.46E-01	1.76E-01	7.46E-03	2.37E-01	1.22E-01	5.17E-03	2.67E-01
12/23/02	8:45	2.64E-01	1.13E-02	3.20E-01	2.00E-01	8.50E-03	2.58E-01	1.48E-01	6.25E-03	3.99E-01
12/23/02	9:00	2.86E-01	1.22E-02	3.76E-01	2.07E-01	8.83E-03	2.84E-01	1.72E-01	7.28E-03	4.93E-01
12/23/02	9:15	2.67E-01	1.14E-02	3.89E-01	2.22E-01	9.44E-03	3.17E-01	1.96E-01	8.33E-03	6.22E-01
12/23/02	9:30	2.69E-01	1.15E-02	4.85E-01	2.76E-01	1.18E-02	3.57E-01	2.17E-01	9.25E-03	7.67E-01
12/23/02	9:45	**End portable data measurements.**					4.05E-01	2.26E-01	9.64E-03	1.06E+00
12/23/02	10:00						4.60E-01	2.29E-01	9.76E-03	1.35E+00
12/23/02	10:15						5.19E-01	2.27E-01	9.68E-03	1.67E+00
12/23/02	10:30						5.80E-01	2.20E-01	9.39E-03	1.89E+00
12/23/02	10:45						6.35E-01	2.17E-01	9.26E-03	2.20E+00
12/23/02	11:00						6.92E-01	2.11E-01	8.97E-03	2.48E+00
12/23/02	11:15						7.50E-01	2.05E-01	8.74E-03	2.81E+00
12/23/02	11:30						8.02E-01	1.90E-01	8.10E-03	2.92E+00
12/23/02	11:45						8.50E-01	1.82E-01	7.75E-03	3.04E+00
12/23/02	12:00						8.85E-01	1.74E-01	7.42E-03	3.11E+00
12/23/02	12:15						9.12E-01	1.72E-01	7.33E-03	3.22E+00
12/23/02	12:30						9.26E-01	1.73E-01	7.37E-03	3.32E+00
12/23/02	12:45						9.53E-01	1.73E-01	7.36E-03	3.48E+00
12/23/02	13:00						9.68E-01	1.62E-01	6.89E-03	3.37E+00
12/23/02	13:15						9.83E-01	1.63E-01	6.95E-03	3.43E+00
12/23/02	13:30						9.84E-01	1.60E-01	6.80E-03	3.31E+00
12/23/02	13:45						9.80E-01	1.60E-01	6.81E-03	3.18E+00
12/23/02	14:00						9.86E-01	1.55E-01	6.59E-03	3.11E+00
12/23/02	14:15						9.85E-01	1.53E-01	6.52E-03	2.97E+00
12/23/02	14:30						9.85E-01	1.50E-01	6.38E-03	2.67E+00
12/23/02	14:45						9.43E-01	1.47E-01	6.27E-03	2.59E+00
12/23/02	15:00						9.27E-01	1.47E-01	6.26E-03	2.26E+00
12/23/02	15:15						8.94E-01	1.48E-01	6.28E-03	2.11E+00
12/23/02	15:30						8.65E-01	1.48E-01	6.29E-03	2.02E+00
12/23/02	15:45						8.29E-01	1.49E-01	6.34E-03	1.74E+00

Date	Time	pressure differential	pressure differential	multiplier	Case Ia	Case Ib	Case IIa	Case IIb	Case IIIa
12/23/02	0:00	7.79E-02			8.53E-04		1.07E-03		1.24E-03
12/23/02	0:15	7.59E-02			8.31E-04		1.04E-03		1.21E-03
12/23/02	0:30	7.42E-02			8.13E-04		1.02E-03		1.18E-03
12/23/02	0:45	7.08E-02			7.76E-04		9.72E-04		1.13E-03
12/23/02	1:00	6.72E-02			7.35E-04		9.21E-04		1.07E-03
12/23/02	1:15	6.79E-02			7.43E-04		9.32E-04		1.08E-03
12/23/02	1:30	6.56E-02			7.19E-04		9.01E-04		1.05E-03
12/23/02	1:45	6.29E-02			6.88E-04		8.63E-04		1.00E-03
12/23/02	2:00	6.44E-02			7.06E-04		8.84E-04		1.03E-03
12/23/02	2:15	6.33E-02			6.93E-04		8.68E-04		1.01E-03
12/23/02	2:30	6.80E-02			7.44E-04		9.33E-04		1.08E-03
12/23/02	2:45	6.46E-02			7.08E-04		8.87E-04		1.03E-03
12/23/02	3:00	6.41E-02			7.02E-04		8.79E-04		1.02E-03
12/23/02	3:15	5.95E-02			6.51E-04		8.16E-04		9.48E-04
12/23/02	3:30	5.94E-02			6.50E-04		8.14E-04		9.46E-04
12/23/02	3:45	6.01E-02			6.59E-04		8.25E-04		9.59E-04
12/23/02	4:00	6.34E-02			6.94E-04		8.70E-04		1.01E-03
12/23/02	4:15	6.15E-02			6.73E-04		8.44E-04		9.80E-04
12/23/02	4:30	6.12E-02			6.70E-04		8.39E-04		9.75E-04
12/23/02	4:45	6.00E-02			6.57E-04		8.23E-04		9.56E-04
12/23/02	5:00	5.84E-02			6.40E-04		8.02E-04		9.31E-04
12/23/02	5:15	5.94E-02			6.51E-04		8.15E-04		9.47E-04
12/23/02	5:30	5.79E-02			6.34E-04		7.95E-04		9.23E-04
12/23/02	5:45	5.62E-02			6.15E-04		7.71E-04		8.96E-04
12/23/02	6:00	5.96E-02			6.52E-04		8.17E-04		9.49E-04
12/23/02	6:15	5.44E-02			5.96E-04		7.47E-04		8.68E-04
12/23/02	6:30	5.38E-02			5.89E-04		7.38E-04		8.57E-04
12/23/02	6:45	5.14E-02			5.63E-04		7.06E-04		8.20E-04
12/23/02	7:00	4.98E-02	5.89E-02	1.19E+00	5.43E-04	6.45E-04	6.80E-04	8.09E-04	7.87E-04
12/23/02	7:15	5.41E-02	5.76E-02	1.07E+00	5.92E-04	6.31E-04	7.42E-04	7.91E-04	8.62E-04
12/23/02	7:30	5.49E-02	5.37E-02	9.78E-01	6.01E-04	5.88E-04	7.54E-04	7.37E-04	8.75E-04
12/23/02	7:45	5.69E-02	6.52E-02	1.15E+00	6.23E-04	7.14E-04	7.80E-04	8.94E-04	9.06E-04
12/23/02	8:00	5.94E-02	7.49E-02	1.26E+00	6.50E-04	8.21E-04	8.15E-04	1.03E-03	9.47E-04
12/23/02	8:15	6.15E-02	1.20E-01	1.96E+00	6.74E-04	1.32E-03	8.44E-04	1.65E-03	9.81E-04
12/23/02	8:30	4.42E-02	1.44E-01	3.26E+00	4.84E-04	1.58E-03	6.07E-04	1.98E-03	7.05E-04
12/23/02	8:45	3.98E-02	2.52E-01	6.33E+00	4.36E-04	2.76E-03	5.46E-04	3.46E-03	6.34E-04
12/23/02	9:00	3.98E-02	3.21E-01	8.07E+00	4.35E-04	3.52E-03	5.46E-04	4.40E-03	6.34E-04
12/23/02	9:15	4.98E-02	4.26E-01	8.55E+00	5.45E-04	4.66E-03	6.83E-04	5.84E-03	7.94E-04
12/23/02	9:30	2.86E-02	5.50E-01	1.92E+01	3.13E-04	6.02E-03	3.92E-04	7.55E-03	4.56E-04
12/23/02	9:45	1.54E-02	Complete evaporation		1.69E-04		2.12E-04		2.46E-04
12/23/02	10:00	7.35E-03			8.05E-05		1.01E-04		1.17E-04
12/23/02	10:15	1.85E-02			2.03E-04		2.54E-04		2.96E-04
12/23/02	10:30	1.43E-02			1.56E-04		1.96E-04		2.27E-04
12/23/02	10:45	2.18E-02			2.38E-04		2.99E-04		3.47E-04
12/23/02	11:00	1.61E-02			1.77E-04		2.21E-04		2.57E-04
12/23/02	11:15	3.54E-03			3.88E-05		4.86E-05		5.64E-05
12/23/02	11:30	1.09E-02			1.19E-04		1.49E-04		1.74E-04
12/23/02	11:45	1.31E-02			1.44E-04		1.80E-04		2.09E-04
12/23/02	12:00	2.43E-02			2.66E-04		3.33E-04		3.87E-04
12/23/02	12:15	3.32E-02			3.63E-04		4.55E-04		5.29E-04
12/23/02	12:30	3.33E-02			3.65E-04		4.57E-04		5.31E-04
12/23/02	12:45	3.42E-02			3.75E-04		4.70E-04		5.46E-04
12/23/02	13:00	3.51E-02			3.85E-04		4.82E-04		5.60E-04
12/23/02	13:15	4.32E-02			4.73E-04		5.93E-04		6.88E-04
12/23/02	13:30	3.89E-02			4.26E-04		5.34E-04		6.20E-04
12/23/02	13:45	3.76E-02			4.12E-04		5.16E-04		6.00E-04
12/23/02	14:00	3.47E-02			3.80E-04		4.77E-04		5.54E-04
12/23/02	14:15	3.67E-02			4.01E-04		5.03E-04		5.84E-04
12/23/02	14:30	4.51E-02			4.94E-04		6.19E-04		7.19E-04
12/23/02	14:45	4.07E-02			4.46E-04		5.59E-04		6.50E-04
12/23/02	15:00	3.99E-02			4.37E-04		5.48E-04		6.37E-04
12/23/02	15:15	4.42E-02			4.84E-04		6.06E-04		7.04E-04
12/23/02	15:30	4.08E-02			4.47E-04		5.60E-04		6.51E-04
12/23/02	15:45	4.12E-02			4.51E-04		5.65E-04		6.57E-04

Date	Time	Case IIIb
12/23/02	0:00	
12/23/02	0:15	
12/23/02	0:30	
12/23/02	0:45	
12/23/02	1:00	
12/23/02	1:15	
12/23/02	1:30	
12/23/02	1:45	
12/23/02	2:00	
12/23/02	2:15	
12/23/02	2:30	
12/23/02	2:45	
12/23/02	3:00	
12/23/02	3:15	
12/23/02	3:30	
12/23/02	3:45	
12/23/02	4:00	
12/23/02	4:15	
12/23/02	4:30	
12/23/02	4:45	
12/23/02	5:00	
12/23/02	5:15	
12/23/02	5:30	
12/23/02	5:45	
12/23/02	6:00	
12/23/02	6:15	
12/23/02	6:30	
12/23/02	6:45	
12/23/02	7:00	9.40E-04
12/23/02	7:15	9.18E-04
12/23/02	7:30	8.56E-04
12/23/02	7:45	1.04E-03
12/23/02	8:00	1.19E-03
12/23/02	8:15	1.92E-03
12/23/02	8:30	2.30E-03
12/23/02	8:45	4.01E-03
12/23/02	9:00	5.12E-03
12/23/02	9:15	6.79E-03
12/23/02	9:30	8.77E-03
12/23/02	9:45	
12/23/02	10:00	
12/23/02	10:15	
12/23/02	10:30	
12/23/02	10:45	
12/23/02	11:00	
12/23/02	11:15	
12/23/02	11:30	
12/23/02	11:45	
12/23/02	12:00	
12/23/02	12:15	
12/23/02	12:30	
12/23/02	12:45	
12/23/02	13:00	
12/23/02	13:15	
12/23/02	13:30	
12/23/02	13:45	
12/23/02	14:00	
12/23/02	14:15	
12/23/02	14:30	
12/23/02	14:45	
12/23/02	15:00	
12/23/02	15:15	
12/23/02	15:30	
12/23/02	15:45	

Date	Time	Baro1	Vtemp 27	VRH27	EB Temp7	EB Temp8	Vel7	Vel8	TC29	TC30	VRH3
12/23/02	16:00	1016.99	70.50	51.62	102.15	77.88	59.12	35.42	104.35	109.05	18.58
12/23/02	16:15	1016.98	69.75	53.25	98.12	75.38	99.98	86.58	97.16	100.31	19.45
12/23/02	16:30	1017.03	69.52	54.60	94.36	74.81	59.12	41.48	91.59	94.81	21.07
12/23/02	16:45	1016.90	68.96	56.82	90.43	73.21	72.38	47.22	86.73	89.53	23.15
12/23/02	17:00	1016.77	68.23	59.25	88.10	72.42	52.72	52.93	82.05	83.91	24.76
12/23/02	17:15	1016.85	67.22	61.67	84.28	70.94	44.46	31.30	77.25	78.34	26.56
12/23/02	17:30	1016.83	64.91	66.92	81.20	69.39	42.40	15.46	72.95	73.52	28.08
12/23/02	17:45	1016.58	62.69	73.58	78.10	67.07	43.37	14.77	69.14	69.30	29.86
12/23/02	18:00	1016.88	60.89	79.40	74.20	65.50	43.03	28.06	65.80	65.63	31.97
12/23/02	18:15	1016.91	59.50	80.97	71.89	63.14	36.66	13.46	63.29	62.95	33.54
12/23/02	18:30	1016.84	60.30	80.68	69.60	63.21	16.40	11.86	61.32	60.78	33.64
12/23/02	18:45	1016.80	61.14	79.40	68.03	63.21	14.29	11.77	59.78	59.10	32.02
12/23/02	19:00	1016.95	61.64	76.74	66.46	63.20	21.07	14.39	58.48	57.89	32.74
12/23/02	19:15	1017.12	61.44	79.02	65.70	62.47	11.70	11.15	57.77	57.08	31.71
12/23/02	19:30	1016.92	61.20	80.46	64.13	62.44	17.32	13.51	57.24	56.42	34.05
12/23/02	19:45	1016.86	60.83	81.99	64.15	61.64	15.97	15.05	56.66	56.04	33.35
12/23/02	20:00	1016.69	60.62	82.67	62.57	61.64	25.24	10.29	56.27	55.60	34.27
12/23/02	20:15	1016.68	60.15	84.65	62.58	60.86	13.23	12.85	55.92	55.27	35.02
12/23/02	20:30	1016.53	59.81	86.35	61.79	60.04	34.40	29.89	55.57	55.02	35.72
12/23/02	20:45	1016.52	59.57	88.15	61.79	60.82	33.46	36.75	55.62	55.04	36.75
12/23/02	21:00	1016.41	59.21	89.79	61.03	60.07	24.95	23.74	55.43	54.96	36.46
12/23/02	21:15	1016.40	58.65	92.04	61.00	60.08	17.56	20.41	55.20	54.74	36.43
12/23/02	21:30	1016.04	58.68	92.44	60.26	59.32	22.16	18.46	54.99	54.44	37.37
12/23/02	21:45	1015.73	58.46	93.32	60.20	60.02	29.49	19.38	55.03	54.59	39.60
12/23/02	22:00	1015.88	58.03	94.84	59.42	60.02	39.17	19.67	55.14	54.42	42.67
12/23/02	22:15	1015.81	57.65	96.20	59.52	60.12	13.84	13.84	54.95	54.34	42.19
12/23/02	22:30	1015.54	57.33	97.19	59.42	60.03	45.54	62.57	54.93	54.18	46.33
12/23/02	22:45	1015.32	57.06	98.12	58.69	60.08	52.83	39.63	55.34	54.29	50.17
12/23/02	23:00	1015.08	57.11	98.91	58.70	59.29	44.09	35.54	55.04	54.22	48.90
12/23/02	23:15	1014.73	57.43	99.10	58.70	60.11	28.12	31.47	55.66	54.81	53.24
12/23/02	23:30	1014.69	57.13	99.28	58.72	59.33	27.47	16.58	55.53	54.55	50.19

Date	Time	VTemp3	Ridge T	Ridge RH	Soffit T	Soffit RH	amb psia	Pws amb	Pw amb	W amb	Pws ridge
12/23/02	16:00	94.36	114.05				14.75	3.69E-01	1.91E-01	8.15E-03	
12/23/02	16:15	92.40	105.31				14.75	3.60E-01	1.92E-01	8.19E-03	
12/23/02	16:30	89.86	99.81				14.75	3.57E-01	1.95E-01	8.34E-03	
12/23/02	16:45	87.38	94.53				14.75	3.51E-01	1.99E-01	8.52E-03	
12/23/02	17:00	85.10	88.91				14.75	3.42E-01	2.03E-01	8.66E-03	
12/23/02	17:15	82.67	83.34				14.75	3.30E-01	2.04E-01	8.71E-03	
12/23/02	17:30	80.32	78.52				14.75	3.05E-01	2.04E-01	8.72E-03	
12/23/02	17:45	77.98	74.30				14.74	2.82E-01	2.07E-01	8.88E-03	
12/23/02	18:00	75.78	70.63				14.75	2.63E-01	2.09E-01	8.92E-03	
12/23/02	18:15	73.63	67.95				14.75	2.52E-01	2.04E-01	8.72E-03	
12/23/02	18:30	71.94	65.78				14.75	2.59E-01	2.09E-01	8.94E-03	
12/23/02	18:45	70.09	64.10				14.75	2.67E-01	2.12E-01	9.07E-03	
12/23/02	19:00	68.62	62.89				14.75	2.72E-01	2.14E-01	9.16E-03	
12/23/02	19:15	67.55	62.08				14.75	2.70E-01	2.13E-01	9.12E-03	
12/23/02	19:30	66.43	61.42				14.75	2.67E-01	2.15E-01	9.21E-03	
12/23/02	19:45	65.86	61.04				14.75	2.64E-01	2.16E-01	9.26E-03	
12/23/02	20:00	65.36	60.60				14.75	2.62E-01	2.17E-01	9.27E-03	
12/23/02	20:15	64.80	60.27				14.75	2.58E-01	2.18E-01	9.34E-03	
12/23/02	20:30	64.40	60.02				14.74	2.55E-01	2.20E-01	9.42E-03	
12/23/02	20:45	64.13	60.04				14.74	2.52E-01	2.23E-01	9.53E-03	
12/23/02	21:00	63.81	59.98				14.74	2.49E-01	2.24E-01	9.59E-03	
12/23/02	21:15	63.43	59.74				14.74	2.44E-01	2.25E-01	9.63E-03	
12/23/02	21:30	63.21	59.44				14.74	2.45E-01	2.26E-01	9.69E-03	
12/23/02	21:45	63.05	59.59				14.73	2.43E-01	2.26E-01	9.71E-03	
12/23/02	22:00	62.99	59.42				14.73	2.39E-01	2.27E-01	9.72E-03	
12/23/02	22:15	62.75	59.34				14.73	2.36E-01	2.27E-01	9.72E-03	
12/23/02	22:30	62.69	59.18				14.73	2.33E-01	2.26E-01	9.71E-03	
12/23/02	22:45	62.91	59.29				14.73	2.31E-01	2.26E-01	9.71E-03	
12/23/02	23:00	62.72	59.22				14.72	2.31E-01	2.29E-01	9.81E-03	
12/23/02	23:15	62.83	59.81				14.72	2.34E-01	2.32E-01	9.95E-03	
12/23/02	23:30	62.78	59.55				14.72	2.31E-01	2.30E-01	9.86E-03	

Date	Time	Pw ridge	W ridge	Pws soffit	Pw soffit	W soffit	Pws VRH3	Pw VRH3	W VRH3	Pws shingle est
12/23/02	16:00						8.00E-01	1.49E-01	6.33E-03	1.43E+00
12/23/02	16:15						7.53E-01	1.46E-01	6.24E-03	1.11E+00
12/23/02	16:30						6.96E-01	1.47E-01	6.24E-03	9.45E-01
12/23/02	16:45						6.43E-01	1.49E-01	6.35E-03	8.05E-01
12/23/02	17:00						5.98E-01	1.48E-01	6.31E-03	6.75E-01
12/23/02	17:15						5.53E-01	1.47E-01	6.26E-03	5.65E-01
12/23/02	17:30						5.13E-01	1.44E-01	6.13E-03	4.83E-01
12/23/02	17:45						4.75E-01	1.42E-01	6.04E-03	4.20E-01
12/23/02	18:00						4.41E-01	1.41E-01	6.01E-03	3.71E-01
12/23/02	18:15						4.11E-01	1.38E-01	5.86E-03	3.39E-01
12/23/02	18:30						3.88E-01	1.31E-01	5.55E-03	3.14E-01
12/23/02	18:45						3.64E-01	1.17E-01	4.96E-03	2.96E-01
12/23/02	19:00						3.47E-01	1.13E-01	4.82E-03	2.84E-01
12/23/02	19:15						3.34E-01	1.06E-01	4.50E-03	2.76E-01
12/23/02	19:30						3.21E-01	1.09E-01	4.65E-03	2.70E-01
12/23/02	19:45						3.15E-01	1.05E-01	4.46E-03	2.66E-01
12/23/02	20:00						3.10E-01	1.06E-01	4.51E-03	2.62E-01
12/23/02	20:15						3.04E-01	1.06E-01	4.52E-03	2.59E-01
12/23/02	20:30						2.99E-01	1.07E-01	4.54E-03	2.57E-01
12/23/02	20:45						2.97E-01	1.09E-01	4.63E-03	2.57E-01
12/23/02	21:00						2.93E-01	1.07E-01	4.54E-03	2.56E-01
12/23/02	21:15						2.89E-01	1.05E-01	4.48E-03	2.54E-01
12/23/02	21:30						2.87E-01	1.07E-01	4.56E-03	2.51E-01
12/23/02	21:45						2.86E-01	1.13E-01	4.81E-03	2.53E-01
12/23/02	22:00						2.85E-01	1.22E-01	5.18E-03	2.51E-01
12/23/02	22:15						2.83E-01	1.19E-01	5.07E-03	2.50E-01
12/23/02	22:30						2.82E-01	1.31E-01	5.56E-03	2.49E-01
12/23/02	22:45						2.84E-01	1.43E-01	6.08E-03	2.50E-01
12/23/02	23:00						2.82E-01	1.38E-01	5.89E-03	2.49E-01
12/23/02	23:15						2.83E-01	1.51E-01	6.44E-03	2.55E-01
12/23/02	23:30						2.83E-01	1.42E-01	6.06E-03	2.52E-01

Date	Time	pressure differential	pressure differential	multiplier	Case Ia	Case Ib	Case IIa	Case IIb	Case IIIa
12/23/02	16:00	4.20E-02			4.60E-04		5.77E-04		6.70E-04
12/23/02	16:15	4.53E-02			4.96E-04		6.22E-04		7.23E-04
12/23/02	16:30	4.85E-02			5.31E-04		6.66E-04		7.73E-04
12/23/02	16:45	5.02E-02			5.50E-04		6.89E-04		8.01E-04
12/23/02	17:00	5.44E-02			5.96E-04		7.47E-04		8.67E-04
12/23/02	17:15	5.66E-02			6.20E-04		7.77E-04		9.03E-04
12/23/02	17:30	6.00E-02			6.57E-04		8.23E-04		9.57E-04
12/23/02	17:45	6.57E-02			7.20E-04		9.02E-04		1.05E-03
12/23/02	18:00	6.75E-02			7.39E-04		9.26E-04		1.08E-03
12/23/02	18:15	6.61E-02			7.24E-04		9.07E-04		1.05E-03
12/23/02	18:30	7.85E-02			8.59E-04		1.08E-03		1.25E-03
12/23/02	18:45	9.53E-02			1.04E-03		1.31E-03		1.52E-03
12/23/02	19:00	1.01E-01			1.10E-03		1.38E-03		1.60E-03
12/23/02	19:15	1.07E-01			1.17E-03		1.47E-03		1.71E-03
12/23/02	19:30	1.06E-01			1.16E-03		1.45E-03		1.69E-03
12/23/02	19:45	1.11E-01			1.22E-03		1.53E-03		1.78E-03
12/23/02	20:00	1.11E-01			1.21E-03		1.52E-03		1.76E-03
12/23/02	20:15	1.12E-01			1.22E-03		1.53E-03		1.78E-03
12/23/02	20:30	1.13E-01			1.24E-03		1.55E-03		1.80E-03
12/23/02	20:45	1.14E-01			1.24E-03		1.56E-03		1.81E-03
12/23/02	21:00	1.17E-01			1.28E-03		1.60E-03		1.86E-03
12/23/02	21:15	1.19E-01			1.31E-03		1.64E-03		1.90E-03
12/23/02	21:30	1.19E-01			1.30E-03		1.63E-03		1.89E-03
12/23/02	21:45	1.13E-01			1.24E-03		1.56E-03		1.81E-03
12/23/02	22:00	1.05E-01			1.15E-03		1.44E-03		1.67E-03
12/23/02	22:15	1.07E-01			1.18E-03		1.47E-03		1.71E-03
12/23/02	22:30	9.58E-02			1.05E-03		1.31E-03		1.53E-03
12/23/02	22:45	8.38E-02			9.18E-04		1.15E-03		1.34E-03
12/23/02	23:00	9.06E-02			9.92E-04		1.24E-03		1.44E-03
12/23/02	23:15	8.08E-02			8.85E-04		1.11E-03		1.29E-03
12/23/02	23:30	8.76E-02			9.59E-04		1.20E-03		1.40E-03

Date	Time	Case IIIb
12/23/02	16:00	
12/23/02	16:15	
12/23/02	16:30	
12/23/02	16:45	
12/23/02	17:00	
12/23/02	17:15	
12/23/02	17:30	
12/23/02	17:45	
12/23/02	18:00	
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12/23/02	20:45	
12/23/02	21:00	
12/23/02	21:15	
12/23/02	21:30	
12/23/02	21:45	
12/23/02	22:00	
12/23/02	22:15	
12/23/02	22:30	
12/23/02	22:45	
12/23/02	23:00	
12/23/02	23:15	
12/23/02	23:30	

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BIOGRAPHICAL SKETCH

Wendell A. Porter was born on the 27th of August 1956, in Akron, Ohio. He attended Cypress Lake High School in Ft. Myers, Florida, graduating in 1974. After attending Edison Community College in Ft. Myers, he transferred to the University of Central Florida, where he graduated in 1979 with a Bachelor of Science degree in Engineering. He furthered his education by completing Master of Science requirements in Engineering in 1981 at North Carolina State University. He then worked in a variety of professional engineering jobs for the next 13 years until 1994 when he accepted a position with the Florida Energy Extension Service at the University of Florida. In 1999 he was persuaded to return to the University of Florida in an additional capacity as a student to pursue a Doctor of Philosophy under the supervision of Dr. Ray Bucklin.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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